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CARBON DIOXIDE ERUPTIONS FROM COAL SEAMS IN LOWER SILESIA.[1]

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COAL seams exhale gases among which methane and carbon dioxide are most important. These two gases may erupt suddenly from the seam and cause great accidents. Catastrophes caused by carbon dioxide are rare and fortunately restricted to few districts only, but methane appears in many coal mines and may cause mine explosions on account of its inflammatory nature. Carbon dioxide eruptions occur primarily in two districts, in Lower Silesia in Germany and in the Department of Gard in southern France. Smaller eruptions occur in the interior and in the northern portion of the French central plateau (Basin of Single and Basin of Brassac). They occur also less frequently in the Basin of Mahrisch-Ostrau in Bohemia. In other coal basins they seem to be unknown.

If human beings breathe air containing from 2 to 7 per cent. of carbon dioxide they are stimulated; breathing of air containing 10 per cent. or more carbon dioxide causes fainting. If a miner faints and sinks to the ground he falls into a stronger mixture of carbon dioxide and suffocates, since carbon dioxide being heavier than air sinks to the lowest places.

Carbon dioxide is found in every coal mine in small quantities, and it is more common in brown coal mines than in bituminous

[1] Presidential Address. Society of Economic Geologists, New York meeting, Dec. 29, 1935.

mines. It originates through the slow oxidation of coal, through the breathing of men, through the burning of lamps, and as an after-effect of mine gas explosions. These small amounts in

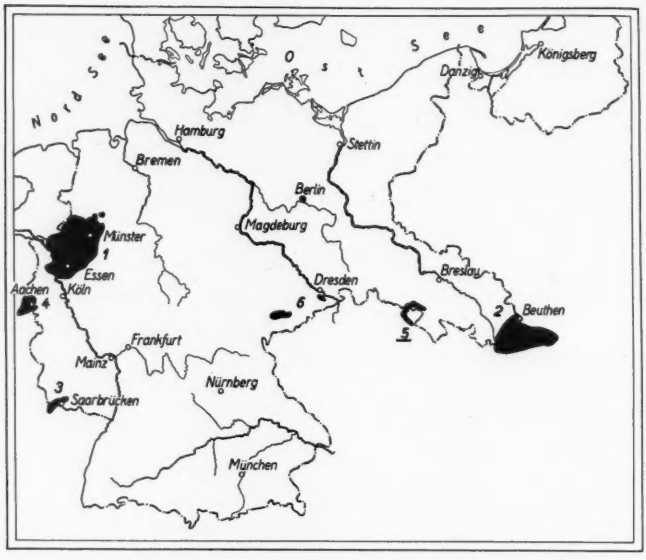

FIG. 1. Map of Germany showing the bituminous coal fields. Numbers are in order of decreasing output: 1. Westphalia; 2. Upper Silesia; 3. Saar; 4. Aachen; 5. Lower Silesia; 6. Saxony.

general are harmless, and are carried away by ventilation. But eruptions of the gas, which suddenly fill entire rooms with carbon dioxide, are dangerous.

Carbon dioxide eruptions occur in Germany in Lower Silesia in the regions of Waldenburg and Neurode. Of these we shall speak here.

The bituminous coal basin of Lower Silesia is located partly in Germany and partly in Bohemia. The Bohemian portion is of no great importance and has no carbon dioxide eruptions. The region of Waldenburg is situated in the north, and the region of

Neurode in the southeast. The coal belongs in the Upper Carboniferous, which rests unconformably upon the Lower Carboniferous. The seams average in thickness from 0.8 to 1.5 meters.

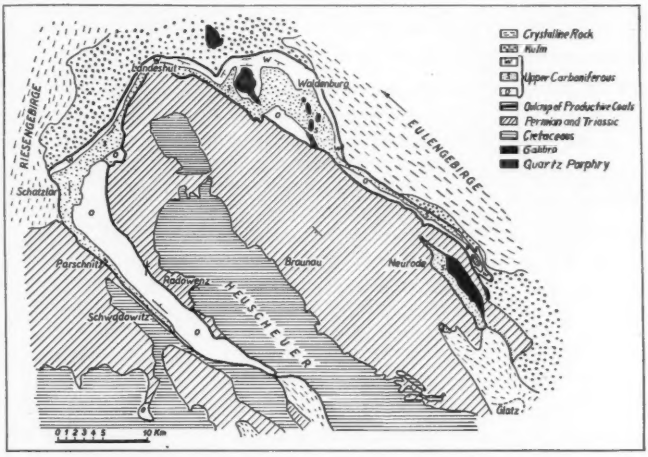

FIG. 2. Geologic map of Lower Silesia coal field.

The yearly production amounts to 5.5 million tons. Carboniferour porphyries and melaphyres are present, and above the Carboniferous lies Permian (Rotliegendes) with quartz-porphyry.

The eruptions have increased in violence as mining has progressed; that is, as greater depth has been reached. The first eruption occurred in 1894. It was at the time quite inexplicable. Twelve years later (1906) two other eruptions occurred, and by 1926, 438 eruptions had taken place, which had ejected 45,000 tons of coal out of the seams. During the latter part of these years the most violent eruptions occurred in the region of Neurode. There, the Ruben group of mines had its first eruption in 1908, its second in 1911, and there were 427 explosions up to June 9, 1931. In the Wenzeslaus mine, in the district of Neurode, there occurred on July 9, 1930, the most disastrous explosion, in which 150 lives were lost.

Carbon dioxide is in coal at the places of eruption under a pressure that increases with depth. If a relief of pressure is brought about slowly through the mining of the coal, carbon dioxide emanates either slowly and unnoticeably, or in the form of periodical blasts or sudden explosions. Carbon dioxide which slowly and continuously emanates is not dangerous because the miners in the carbon dioxide districts are prepared for it, and ventilation removes it. The following data illustrate how large this quantity may be: The shafts of the Wenzeslaus mine between 1921 and 1925 gave off on an average an amount of carbon dioxide such that 18.5 cubic meters of the gas came out with each ton of coal. Some people believe that the carbon dioxide quantity which is freed during a great eruption is still larger, but this is not the case, if calculated with regard to the tons of coal thrown out. An eruption distinguishes itself from slow gas delivery only through the rapidity of carbon dioxide emanation.

Investigations in coal petrography have shown that coal which is inclined to have explosions is greatly fragmented. This feature seems to be a prerequisite for an eruption. The mining of such seams always produces coal screenings. In the Ruben mine near Neurode, a screening is produced of which 75 per cent. is of a size of less than 10 mm. (up to 90 per cent. below 30 mm.).

How does the carbon dioxide occur in the coal seams? It can be contained in visible fissures and pores but also in microscopically and ultra-microscopically pores, as a gas which is condensed in proportion to gas pressure. On the other hand, carbon dioxide may be adsorbed on the surface of the coal, especially fossil charcoal, which is very common in the Lower Silesia seams. Or the carbon dioxide is absorbed and forms a solid solution with the contents of the coal, especially with the vitrain, and is released whenever the gas pressure decreases.

Experiments have been made concerning the absorption and release of carbon dioxide in coal by O. Ruff using coals from Upper and Lower Silesia. It has been determined that one ton of coal, if placed in pure carbon dioxide under a pressure of one atmosphere, and at 21° C., will hold four cubic meters of carbon di-

oxide. The coals absorbed three cubic meters more of carbon dioxide if exposed to a pressure of two atmospheres. The ability of the coal to absorb gas rises with increased pressure at first rapidly, later more slowly. The curve of increasing gas absorption under increasing pressure has the form of a parabola. If the pressure is decreased, the gases again emanate.

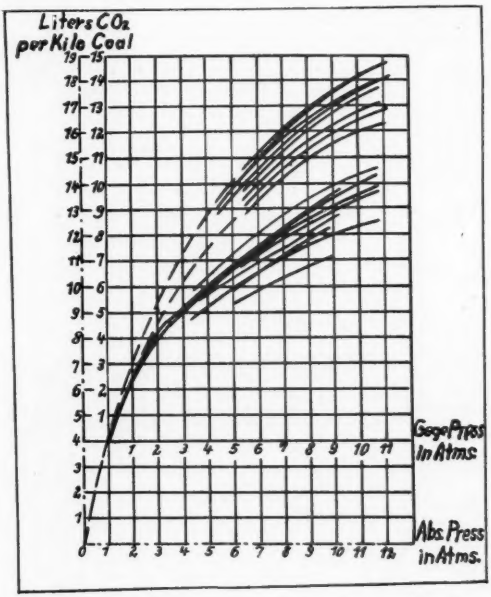

FIG. 3. Absorption of carbon dioxide in Lower Silesian coals at 21° C. (After O. Ruff.)

The following is of importance: The size of the grain of coal influences the rapidity of absorption and of emanation of carbon dioxide. Powdered coal absorbs carbon dioxide rapidly and eliminates it quickly. Nut-size coal does it more slowly. After a few hours the former is in a state of stability with the carbon dioxide, but the latter reaches that state after days or weeks. Furthermore, it has been shown that coal which is rich in fusain ab-

sorbs and eliminates carbon dioxide very rapidly. Fusain is porous. The fusain content is relatively large in the coals of Lower Silesia, but generally it is not greater in the seams of the

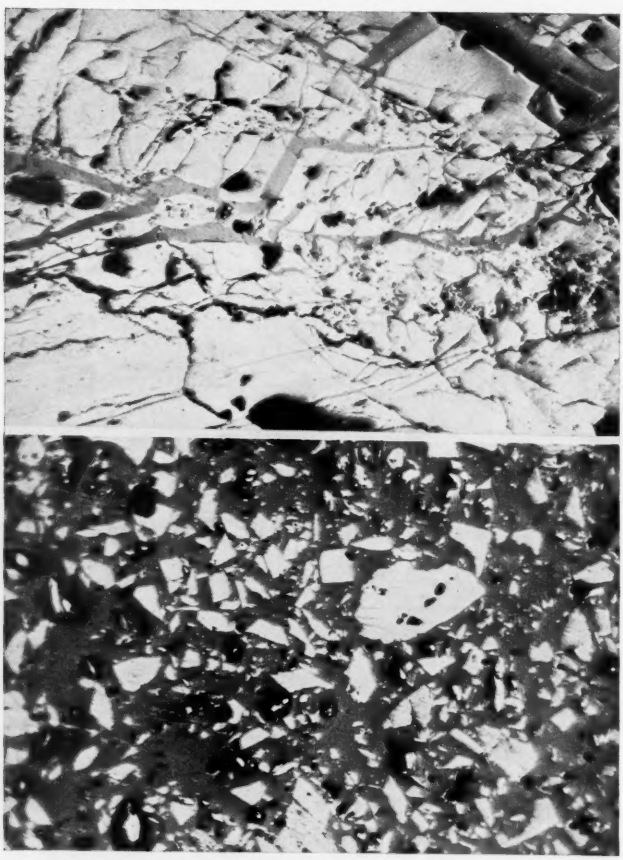

FIG. 4 (Upper). Polished section of Lower Silurian coal seam, showing cracked character of coal before explosion. × 155 (White = coal, gray = wax filling cracks).

FIG. 5 (Lower). Polished section of coal dust after explosion. × 155 (White angular fragments = vitrain; white fragments with shadows = fusain; gray = mounting medium).

carbon dioxide region than outside of it. *The experiments of Ruff indicate that the carbon dioxide is in solid solution with the vitrain of the coal.*[2] It seems that the large surface which is created through the breaking up of the coal by tectonic movements is a necessary condition for the sudden emanation of carbon dioxide in carbon dioxide eruptions. Before some eruptions, the coal suddenly loses its lustre and appears dull. Then carbon dioxide breaks out from an eruption channel. In many cases the coal begins to "work" before an eruption. This occurs with a distinctly audible noise and under lowering of temperature in the coal face. Other eruptions occur without warning. During an eruption, a solid coal face may be pushed into the workings. For instance, during the great catastrophe of 1930, a coal block of 16.5 meters length, 8 meters width, and 1.5 meters height, 240 tons in weight, was moved foward in a solid mass. If one compares the quantity of coal which has been thrown out during an eruption with the size of the cavity that was formed, one has to assume that the walls of the cavity have moved forward, because this cavity is always smaller than the corresponding quantity of thrown-out coal, even if the coefficient of expansion of breaking is considered. Also drill holes from which carbon dioxide emanates become more narrow, just as if the coal were swelling.

During the great catastrophe of the Wenzeslaus mine in 1930, 1,757 tons of coal and 268 tons of rock were ejected. During the catastrophe of the Ruben mine in 1931, 140 tons of dry coal dust were found on the fourth level alone. The size of this coal dust can be seen from the sieve analysis:

Size over 0.5 mm.	3.48%
Size 0.5 to 0.25 mm.	6.58
Size 0.25 to 0.15 mm.	13.00
Size 0.15 mm. to 0.075	37.89
Below size 0.075 mm.	38.50

Therefore, more than three-fourths of the coal dust which filled the fourth level was of a grain size below 0.15 mm. During an

[2] Ruff has also determined the solubility of methane in coal. The solubility of methane is considerably less than that of carbon dioxide. Also due to the lower specific gravity of methane, the mechanical effects of methane explosions are less than those of carbon dioxide.

eruption the coal is broken up into finest dust. But how can we explain that during the catastrophe in 1930 a block of coal of 240 tons weight had been moved forward without being broken? This was only made possible through the pressure of removing the coal, that is, through the pressure of the unsupported roof upon the face of the coal, the latter had become so solidified that it was pushed forward through the pressure of the gas behind it, as a solid block.

The pressure of a carbon dioxide eruption is usually overrated. It has never been measured. In many cases the carbon dioxide seems to become free only under a pressure of from two to three atmospheres, and seems to escape at the rate of two to three hundred meters per second. Observations during removal of the debris made it clear that sometimes much greater pressure, at least as a result of the explosion, must have existed. For example, loaded coal wagons have been known to be lifted up through gas pressure. During an eruption in the region of the Ida mine, pump water under a pressure of 20 atmospheres, and machinery was pushed back by the carbon dioxide.

Also, the following is characteristic: The positions of the victims and of ejected coal often gives the impression as if the weight of the bodies had been reduced. Men who held themselves on the mine props and who were suffocated were sometimes lifted up and carried by the loose coal, but not covered by it. During an eruption in the Ruben mine a large block of rock of at least a ton weight was carried away by the ejected coal and was moved around a corner, at a right angle, for a distance of about 20 meters along the main entry of the mine without damaging the workings.

The form of the cavity which is developed by the explosion is worthy of note. Many are joined by means of a neck-like constriction; there are many irregular forms, which remind one of a hand with five fingers.

The explosions are caused by reduction of compression, caused by mining. The released carbon dioxide streams out, expands, uses up heat, and lowers the temperature. The refrigeration is

great enough to be felt through one's boots. In drill holes, temperatures of one degree Centigrade have been measured. In large explosions the ejected coal often remains ice cold for days, because it continues to emit gas.

The carbon dioxide has been introduced into the coal; it is thus a foreign substance of the seam. It is of the same origin as the carbon dioxide of the mineral springs of Waldenburg, which come to the surface in the neighborhood of the mine fields, for example, in Salzbrunn, in Charlottebrunn, and in Altreichenau. It is probably the exhalation of the magma which gave rise also to the recent volcanic rocks (basalt) of the surrounding territory. The carbon dioxide has nothing to do with old Carboniferous and Permian quartz-porphyry, which form intrusions throughout the coal territory. Carbon dioxide makes its way through the fissures from below. It could collect in porous sandstones and in fractured rocks, as also in fractured quartz-porphyries. If coal seams were associated with porous sandstones and cracked rocks, then carbon dioxide could force itself out of the cracks and out of the porous sandstone into the coal, by which it has been finally absorbed.

Carbon dioxide eruptions cannot be prevented, but catastrophies can be avoided. The districts are known in which seams are inclined to erupt, and it is important to recognize the danger of a carbon dioxide eruption. There are eruptions which announce themselves beforehand. If mine lamps are extinguished in the depressed places of workings, if the drill holes exhale gases which put out lamps, and if these gases have a low temperature, an acid and prickling taste, and if they make breathing more difficult, then under special precautions only is it permitted to continue mining. Sometimes an eruption occurs without warning. For example, in the Ruben mine, a seam piece, 30 by 20 meters in plan, had been exposed there for years; suddenly on September 2, 1925, an eruption occurred during which five men and a horse were suffocated. It shows that free-standing smaller parts of coal seams still possess the danger of explosion.

As a rule catastrophies can be prevented if the eruptions are

released before they release themselves. This is brought about by tremor shots from covered shooting places. These shots can be ignited at different places simultaneously by electricity. The crew of the mine section retreat then behind covers which are connected with each other and with the surface by telephone.

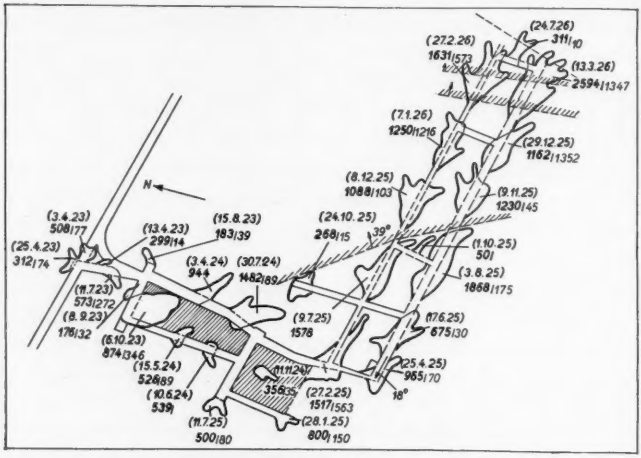

FIG. 6. Carbon dioxide eruptions in Anton seam, Consolidated Ruben Mine, near Neurode, Lower Silesia, from April 3, 1923, to July 24, 1926. (After Rademacher.) Solid lines show extent of eruptions; numbers in parentheses are dates of eruptions; heavy numbers are cars of coal ejected by the eruptions; light numbers are cars of rock ejected by the eruptions.

Mines with coal seams subject to eruption are, of course, more expensive to mine. It is necessary to build special entries for ventilation. Mining laws are very strict about this. Every kind of mining has to be avoided which could bring about a considerable tremor because thereby an eruption might be instigated. Therefore, snubbing of the coal is prohibited in seams that are inclined to eruptions. Coal which could easily be obtained with the pick must be shot, so that coal and rock become mixed. Special places for shooting the coal must be arranged, where the

miners can take proper cover. The cover doors have to be so constructed that they can resist a pressure of four to five atmospheres. Because it is expensive continually to build new covers near the place of shooting, the men are often removed 500 meters

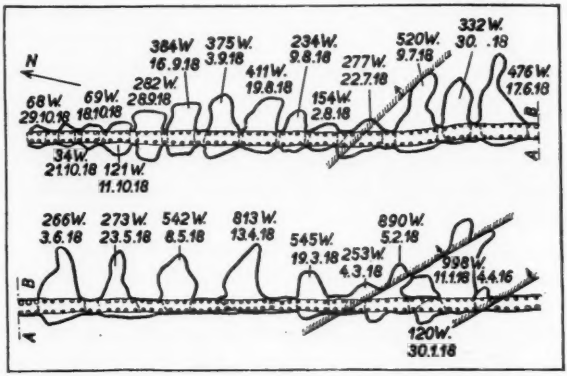

FIG. 7. Carbon dioxide eruptions in Ferdinand seam, Consolidated Ruben Mine, near Neurode, Lower Silesia. (After Rademacher.) Solid lines show extent of eruptions; upper numbers are cars of coal and rock ejected by the eruptions; lower numbers are dates of eruptions.

from the work face. The workman, therefore, loses time, often one and a half hours per shift. All this makes mining more expensive, even if eruptions do not take place. In seams threatened by eruptions, the seam entrance must be traveled repeatedly.

In addition to the above mentioned districts, carbon dioxide eruptions occur in Germany in the potash district of Werra Valley. They appear in a deposit of sylvanite which has become porous by leaching and which is well sealed by clay above and below. In the mines of Desdemona and Heiligenroda, up to 7,000 tons of potash salts have been thrown out. There the origin of the carbon dioxide is traced back to young basaltic rocks intruded into the Permian potash deposits.

SUMMARY

Bituminous coal seams contain large quantities of carbon dioxide in many places in Lower Silesia, Germany. During mining, this carbon dioxide is released through reduction of pressure. This sometimes occurs suddenly, and the released gas blows many hundreds of tons of coal into coal dust, which is spread over the mine workings. The carbon-dioxide containing seams of Lower Silesia are highly fragmented. The fragmentation is a prerequisite for the sudden release of carbon dioxide. The carbon dioxide is a constituent which is foreign to the coal; it has arisen along fissures from which it entered into the coal, forming a solid solution with the vitrain of the coal.

FREIBERG, SAXONY, GERMANY,
May 18, 1936.

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SOME NOTES ON THE ORIGIN OF PYRITIC COPPER DEPOSITS OF THE MESOTHERMAL TYPE.

JOSEPH E. A. KANIA.[1]

INTRODUCTION.

FOR MANY years the subject of the origin of ore deposits, more particularly the mode of transportation and deposition, has been a contentious one. This is not strange in view of the fact that the solution lies in reasoning back from visible results as shown to us in ore deposits rather than observing the process itself. There are those who argue that, because of the very nature of the processes involved, we shall never be able to simulate them closely enough to make our experimental results of any practical value, while others argue that in making certain seemingly reasonable assumptions, and using these as a starting point, we can, by means of extensive experiments, arrive at an approximation of the nature of ore-forming processes.

The writer belongs to the latter school of thought, and submits this paper (a brief abstract of a long dissertation) in which are summarized the results of a large number of experiments regarding one type of deposit only, with the hope that the factual information and the writer's deductions therefrom may be of some use to other students of this fascinating subject.

Because of the promising results obtained, the writer subsequently attempted to carry these studies further than herein indicated, but a series of economic reverses frustrated that attempt for the time being.

Acknowledgments.

During the years 1928 to 1930, the writer was a graduate student in the Department of Geology at the Massachusetts In-

[1] Emmons Memorial Fellow 1929–1930.

stitute of Technology. In 1929 he was appointed Emmons Memorial Fellow, and as such undertook the problem of investigating experimentally the nature of the origin of copper deposits of the mesothermal type.

The writer gratefully acknowledges the many helpful criticisms and suggestions of Professor Waldemar Lindgren, under whose guidance this paper was prepared. It was following upon a discussion with him that the colloidal sulphide solutions were investigated. The critical discussions of this paper with Dr. W. H. Newhouse of the same department are also gratefully acknowledged.

Thanks are due to Professors Bugbee and C. R. Hayward, and Messrs. R. C. Reed and H. B. Litchman of the Dept. of Mining, Professor M. S. Sherrill and Messrs. J. L. Moore and F. Ebersole of the Dept. of Chemistry for their ready help and permission to use equipment. I wish also to express my gratitude to the three directors of the Emmons Memorial Fellowship Fund.

BIBLIOGRAPHICAL REVIEW.

The field of experimentation dealing with the formation, dispersion, color changes, stability, coagulation and crystallization of metallic sulphide sols, often presumably simulating natural conditions, has claimed a large number of investigators. The following chronologically tabulated summary was prepared to show the data available in the literature from 1910 to 1930 on the subject of colloidal solutions in general and sulphide sols in particular.

Color Changes.

1907.—Concentrated CuS solution changed from brown, in the cold state, to deep green on heating, and to deep olive green when H_2S was passed into the hot solution. The brown hydrosols contained almost entirely submicroscopic particles, green hydrosols much larger ones.[2] Such color changes may be reversible.[3]

[2] Lottermoser, A.: Contribution to the Preparation of Hydro and Organosols of Metal Sulphides. Jour. Prakt. Chem., vol. 75, pp. 293–306, 1907. (From Am. Chem. Soc. Abst.)

[3] Zsigmondy and Kirchner: Zur Erkentnisse der Kolloide. Pp. 147–148.

1920.—Color changes on coagulation of the precipitate depend on the method of coagulation and age of the sulphide and not on the salts employed for precipitation nor upon the nature of the ions that cause it.[4]

1925.—As the diameter of the particles increases, the color of transmitted light goes from greenish blue to green.[5]

1925.—The color depends much on the nature of the material absorbed by the sol or the coagulated mass.[6] The same author quotes Wo. Ostwald's general conclusion that with increasing degree of dispersion (*i.e.* decreasing size of particles) the absorption band of any colloidal solution moves to the shorter wave length.

The above brief summary indicates that size of particles, temperature of solutions, method of coagulation, age of solution and material absorbed apparently all play a part in the color changes of colloidal solutions, although the first factor seems to be the one most effective.

Preparation of Solutions.

In the preparation of colloidal sulphide solutions rarely have experimenters, approaching the subject from the geologist's point of view, prepared such solutions that could properly be called primary ascending sulphide solutions. They have been mainly concerned with the problem of getting sulphide sols from sulphate solutions (thus simulating conditions of essentially secondary downward enrichment) invariably employing H_2S in either liquid or gaseous form. In other cases [7] it is fallaceously argued that, because pyrite is practically insoluble in alkaline solutions, it is improbable that it was carried as an alkali double sulphide unless in enormously concentrated alkali sulphide solutions. Not only

[4] Hahn, F. V. v.: Color Changes during the Coagulation of Sulphide Hydrosols. Kolloid, vol. 2, pp. 27, 172–5, 1920. (From Am. Chem. Soc. Abst.)

[5] Jobst, G.: Theory of the Color of Colloidal Metal Suspensions. Ann. Physik. ser. 4, vol. 76, pp. 863–888, 1925. (From Am. Chem. Soc. Abst.)

[6] Dhar, N. R.: Influence of Adsorption on the Color of Sols and Precipitates. Jour. Phys. Chem., 1925, p. 1394.

[7] Foreman, Fred: Hydrothermal Experiments on Solubility, Hydrolysis and Oxidation of Iron and Copper Sulphides. Econ. Geol., vol. 24, p. 811, 1929.

does this corollary not follow but, as will be shown below, it is a simple matter to prepare alkali double sulphide solutions carrying as high as .182 grams of Fe per liter or .68 grams Zn per liter, and these are not upper limits.

Factors Increasing Stability and Aiding Dispersion.

1914.— (1) $CO_2 + H_2S$ aid dispersion.
(2) K and Na salts, the former being the more active in this respect.
(3) In acid solutions H_2S at high temperatures.[8]
1917.— (4) Increased pressures, up to two atmospheres (with H_2S–ZnS solutions).[9]
1920.— (5) Dilution of sols (for any univalent electrolyte).[10]
(6) Concentration of sol (for any trivalent electrolyte).[11]
(7) Salts of alkali metals at high temperatures.[12]
1921.— (8) Longer treatment of sols with H_2S through sols (for Ag_2S sols).
(9) More rapid passage of H_2S through sols (Ag_2S sols).
(10) Rise in temperature.[13]
1924.—(11) Electrolytes in quantities too small to cause coagulation.[14]
(12) Decreasing valency of electrolyte cation.[15]
(13) Increasing the concentration of a sol increases its stability towards electrolytes.[16]
1925.—(14) Dilution of a sol decreases the precipitation power of any electrolyte.
(15) Increased age of sol (with As_2S_3).[17]

[8] Tolman and Clark: Copper Sulphide. ECON. GEOL., vol. 9, p. 559, 1914.

[9] Young, S. W., and Goddard, W. R.: The Reversibility of Sulphide Sols and the Protective Action of H_2S. Jour. Phys. Chem., vol. 21, p. 1, 1917.

[10] Burton, E. F., and Bishop, E.: Coagulation of Colloidal Solutions by Electrolytes. Jour. Phys. Chem., vol. 24, p. 701, 1920.

[11] Idem, p. 701.

[12] Mukherjee, I. N.: Influence of Temperature on the rate of Coagulation of Arsenious Sulphide Hydrosols. Jour. Chem. Soc., vol. 117, pp. 350–359, 1920.

[13] Hahn, F. V. v.: Preparation of Sols with Gaseous H_2S. Kolloid, vol. 2, pp. 29, 139–45, 1921 (from Am. Chem. Soc. Abstr.).

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[16] Sen, K. C.: On the Stability of Colloidal Solutions. Jour. Phys. Chem., vol. 28, p. 1029, 1924.

[17] Dhar, N. R.: Coagulation of Diluted Sols by Electrolytes, Acclimatization and Behaviour toward Mixed Electrolytes. Jour. Phys. Chem., vol. 29, pp. 435–461, 1925 (from Jour. Chem. Soc. Abst.).

1926.—(16) Most stable gels are relatively dilute and are precipitated from dilute colloidal solutions.[18]

1929.—(17) Saturated solutions of calcium bicarbonate are very ineffective precipitants of colloidal SiO_2.[19]

(18) $CaCO_3$ and CO_2 separately are peptizers of colloidal SiO_2.[20]

(19) Ions of higher valency do not have greater coagulating power on colloidal SiO_2 than ions of lower valency.[21]

(20) Nine parts per million of organic matter is an efficient protector of colloidal SiO_2.[22]

Factors Decreasing Stability.

1914.— (1) Ca and Al salts (chlorides); thus limestone, clay gouge and aluminous matter are good coagulants.

(2) CO_2 without H_2S.[23]

1917.— (3) Repeated coagulation and dispersion.

(4) Probably increased pressures beyond two atmospheres (with H_2S–ZnS solutions).[24]

(5) The relative flocculating powers of chlorides of K, Ca and Al are 1 : 39 : 875.[25]

(6) Sols deprived of H_2S are unstable and will flocculate ultimately spontaneously.[26]

(7) The concentration of electrolyte required to cause coagulation within 24 hours is (1) independent of the origin of the sol, (2) within wide limits independent of the dilution of the sol and (3) independent of the presence or absence of free H_2S.[27]

1924.— (8) Increasing the valency of the electrolyte cation.[28]

(9) HCl, H_2SO_4 and salts of the alkali earth metals.[29]

[18] Boydell, H. C.: Metasomatism. ECON. GEOL., vol. 21, p. 29, 1926.

[19] Moore, E. S., and Maynard, J. E.: Solution, Transportation and Precipitation of Iron and Silica. ECON. GEOL., vol. 24, p. 281, 1929.

[20] Idem, p. 397.

[21] Idem, p. 510.

[22] Idem, p. 516.

[23] Tolman and Clark: *Op. cit.*

[24] Young, S. W., and Goddard, W. R.: *Op. cit.*

[25] Young, S. W., and Neal, R.: Colloidal Solutions of Copper Sulphide. Jour. Phys. Chem., vol. 21, pp. 14–31, 1917.

[26] Idem, p. 31.

[27] Idem, p. 30.

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[29] Mukherjee, I. N.: *Op. cit.*

(10) Decreasing the impurities in a sol.[30]
(11) Dilution of a sol (in general).[31]

1926.—(12) High degree of supersaturation prior to coagulation.[32]

1928.—(13) Diminution of charge and total surface of sol.[33]

1929.—(14) $Ca(HCO_3)_2$ and sea water most effective precipitants of colloidal SiO_2.[34]
(15) $CaCO_3 + CO_2$ precipitate SiO_2 gel.[35]
(16) Changing SiO_2 sol from acid to alkaline increases rate of coagulation.[36]

Notes on Crystallization from Gels.

1910.— (1) Chalcopyrite would not form from solutions of its own composition but all the copper precipitated out first and then the iron.[37]

1913.— (2) Rise in temperature and jarring frequently wholly crystallize a gel.[38]

1914.— (3) Crystallization may be practically simultaneous with the precipitation of the dispersed matter and needs no intervening gel phase.[39]

1917.— (4) Holmes[40] confirmed Dreaper's opinion that diffusion through capillary spaces other than those in a gel may be efficient in aiding crystal formation. He also proved by experiment that in many instances the amorphous or fine grained precipitate formed when two solutions meet acts as a membrane or net work of capillaries retarding further diffusion and favoring the precipitation of more of the precipitate in larger crystalline particles.
(5) $BaSO_4$ is always more coarsely crystalline when precipitated in the presence of an appreciable amount of HCl.[41]

[30] Sen, K. C.: *Op. cit.*
[31] Idem, p. 1035.
[32] Boydell, H. C.: Metasomatism. ECON. GEOL., vol. 21, p. 32, 1926.
[33] Chandhury, S. G.: The Influence of Concentration of a Sol on its Stability. Jour. Phys. Chem., vol. 32, p. 1231, 1928.
[34] Moore, E. S., and Maynard, J. E.: *Op. cit.*, p. 277.
[35] Idem, p. 385.
[36] Idem, p. 511.
[37] Wells, R. C.: The Fractional Precipitation of Sulphides. ECON. GEOL., vol. 5, pp. 1–14, 1910.
[38] Krusch: Zeit. Prakt. Geol., 1913, pp. 506–513.
[39] Tolman and Clark: *Op. cit.*, p. 559.
[40] Holmes, H. N.: The Formation of Crystals in Gels. Jour. Phys. Chem., vol. 21, pp. 709–733, 1917.
[41] Weiser, H. B.: Adsorption by Precipitated $BaSO_4$. Jour. Phys. Chem., vol. 21, pp. 314–333, 1917.

1922.— (6) Electromotive action plays a part in forming crystals from a colloidal system.[42]

1926.— (7) The rate of crystal growth is not dependent on the acidity of the solution but on its concentration (with PbI_2 HgI and $CaCO_3$ crystals).[43]

1927.— (8) Marcasite is deposited in acid solutions, pyrite in neutral to acid solutions and melnikovite (black amorphous FeS_2) in alkaline solutions. Temperature is not an important factor. Optimum conditions for the deposition of marcasite are 1.18 per cent. H_2SO_4 at 100°. Decreasing acidity and raising the temperature give pyrite.[44]

EXPERIMENTS.

The experiments, only the results of which are here summarized, were performed in three stages:

(1) *Preparation of Melts.*—Na_2S fused in a furnace separately with each of the following practically pure minerals: Pyrite, chalcopyrite, sphalerite, silica.

(2) *Extraction of Melts with Water at Various Temperatures.*—At 25 to 32° C. At 95° C. and cooled to 32° C. some hours later. At 95° C. and kept there throughout the experiment. All experiments were carried out at atmospheric pressure, and in contact with various rocks and compounds, namely: Pure powdered $CaCO_3$, greenstone, white marble, lime mudstone, quartzite, carbonaceous shale. CO_2 was added to some of the sols and solutions, whereas H_2S was present in all of them when each melt was extracted with water.

The two hundred and thirty or so separate experiments performed by the writer by no means exhausted all the combinations possible with the above-mentioned number of variables, namely rocks, temperatures, gases, but yielded some unique results.

(3) *Examination of Results Obtained.*—(See summary of results below.) Following the summary of results immediately below, the reader will find in the author's conclusion an attempt to answer these questions.

[42] Kohlschutter, V., and Steck, K.: Crystal Formation in Colloidal Metals. Zeit. Elektro-Chem., vol. 28, pp. 554–568, 1922.

[43] Fisher, L. W., and Simmons, F. L.: Am. Min., 1926, p. 125.

[44] Tarr, W. A.: Alternating Deposition of Pyrite, Marcasite and possibly Melnikovite. Am. Min., 1927, p. 419.

Summary of Results (Na_2S–FeS_2 Solutions and Sols).

The experiments with the various double sulphides are summarized here and under similar subsequent headings.

1. Na_2S–FeS_2 solutions prepared with boiling water and cooled to 32° are more stable at that temperature than solutions prepared with cold water and kept at 32°.

2. Cold, concentrated acid solutions tend to be neutralized in the rocks.

3. Cold, concentrated, alkaline solutions tend to remain alkaline in the rocks, but at 90° become neutral in contact with calcareous rocks and acid in contact with silicious rocks.

4. Cold, concentrated alkaline solutions neutralized with CO_2 become acid in contact with rocks.

5. On the whole dilute solutions at 32° were found to be less stable than concentrated solutions under the same conditions excepting where in contact with a peptizer such as a silicious rock.

6. As the amount of crystalline $CaCO_3$ increases in the rocks in contact with CO_2 charged solutions the latter's stability decreases.

7. The escape of H_2S from solutions is only partly due to a rise in temperature and mainly due to the contained excess of CO_2 forcing the H_2S out of solution at any opportunity producing immediate coagulation of the suspensoid or colloid.

8. Decrease in temperature has a stabilizing rather than a coagulating effect on colloidal sulphide solutions; hence the important factors in coagulation are changes in the chemical and physical state of the rock medium and in the differential pressure rather than in the absolute pressure.

9. FeS_2 sols are far less stable than the corresponding Na_2S–FeS_2 solutions, illustrating the stabilizing effect of the Na_2S in combination with the metal sulphide.

10. Pyrite cubes crystallized

(1) from concentrated alkaline Na_2S–FeS_2 solution in contact with crystalline limestone, at 32°,

(2) from a neutral Na_2S solution in contact with carbonaceous shale heated to 90° and cooled to 32°,

(3) from a concentrated acid, carbonated Na_2S–FeS_2 solution in contact with crystalline limestone at 90°, and

(4) from a dilute, acid carbonated Na_2S–FeS_2 solution in contact with crystalline limestone.

11. Pyrite crystals were derived as stated above, from Na_2S–FeS_2 solutions, but marcasite crystals were derived from FeS_2 sols rather dilute in Na_2S, either acid or alkaline in character and at both 32° and 90° C.

Summary of Results (Na_2S–$CuFeS_2$–FeS_2 Sols).

1. Na_2S fused in combination with metal sulphides and extracted with water stabilized them while removal of the Na_2S by decantation coagulated them.

2. Na_2S solution is very unstable in contact with those of the double sulphides, and when added to sulphide sols was observed to have a coagulating effect on them.

3. Ferrous and copper sulphides (presumably as chalcopyrite) will coagulate in the presence of FeS_2 either in solution as a double sulphide with Na, or as a sol.

4. Na_2S–SiO_2 solutions will coagulate Na_2S–$CuFeS_2$ and FeS_2 sols. The effect of Na_2S–SiO_2 solution on Na_2S–FeS_2 solution was not observed.

5. Chalcopyrite and marcasite crystals formed in a hot CO_2 charged acid sol which later became alkaline.

6. Crystals suggestive of marcasite were seen scattered through the gel in both greenstone and CO_2, and quartzite and CO_2 experiments at 32°. The sols were acid.

Chalcopyrite Crystals.

These were found solidly encrusted on and replacing the limestone in the experiment (lasting 8 days) in which the sol was charged with CO_2. The sol, originally acid with CO_2, was found to be distinctly alkaline when tested at the end of the experiment.

Some of the chalcopyrite crystals attained .1 mm. in size and were developed as sphenoids, the triangular faces being visible in several instances, and Prof. M. J. Buerger noted prism faces truncating the corners. Some of the crystalline limestone pieces covered with this sulphide were embedded in sealing wax and polished. When the polished section was examined, it was found that chalcopyrite distinctly replaced the limestone. The small sulphide grains were partly triangular in section, partly in the shape of skeleton crystals, with hollow centers, but mostly irregularly elongated. They were found to be weakly polarizing and to replace the limestone, being arranged around the calcite grains, and commonly penetrating them. None of the grains showed any colloform structure.

The sulphide was entirely chalcopyrite, which was to be expected since the FeS_2 had been removed by repeated decantations

and only the ferrous and copper sulphides were left in colloidal suspension. There was no gel phase involved in the process, and it is patent from this and the previous experiments in which pyrite crystals formed, that because a sulphide shows no colloform structure is no criterion for saying that it was not deposited from colloidal solution.

Summary of Results (Na_2S-ZnS Sols).

1. Due to the presence of some FeS_2 in the undecanted sols in these experiments the behavior of the Na_2S–ZnS sols without FeS_2 present could not be observed. The fact, however, was revealed that Na_2S–FeS_2 has a coagulating effect on ZnS in suspension.

2. A sol prepared with pure powdered ZnS and ½ N Na_2S solution is very unstable, probably due to the fact that the Na_2S solution in itself is unstable.

3. Na_2S–SiO_2 solution has a coagulating effect on ZnS in suspension.

4. Silicious rocks have a peptizing effect on ZnS in suspension.

5. No definite trend one way or the other was observed when ZnS sol and $CuFeS_2$ sol were mixed. They seemed to go into and out of suspension together, with the Zn probably lagging slightly behind in settling.

6. ZnS seemed somewhat more stable at 90° than at 32°.

Summary of Results (Na_2S-SiO_2 Solutions).

1. Solutions prepared with tap water, probably due to its oxygen content, are decidedly less stable than those prepared with distilled water.

2. Solutions at 90° are less stable than similar solutions at 32°.

3. In the experiments using tap water, the colloidal silica was frequently visible when the solution cleared up, either in suspension, or as an incipient gel at the bottom of the tube.

4. In the experiments using distilled water, no colloidal SiO_2 was observed, due probably, to the dense black Na_2S precipitate wherever the solution cleared up.

As the heavy flocculent Na_2S precipitate masked the colloidal SiO_2 precipitate, it was not possible to watch the latter's behavior, nor observe it in the black amorphous product when the rocks were finally examined. In nature, the supply of carbonated waters is evidently sufficient to convert the Na_2S all into Na_2CO_3 to be carried off in solution, while the silica or sulphide, as the case may be, is deposited without any admixture of its alkali carrier.

DESCRIPTION OF TYPE DEPOSITS.

Jerome, Arizona.[45]

The rocks of the Jerome quadrangle consist of the Yavapai schists (chloritic mica and sericite schists) of Algonkian age, in part of sedimentary origin, intruded by the Algonkian Bradshaw granite followed by calcareous Paleozoic sediments and Tertiary volcanics. Some Tertiary lacustrine deposits also occur.

All of the commercial ore is found in the pre-Cambrian schists. The Paleozoic sediments were laid down on the eroded, already-formed, deposits. These consist of pyritic replacements in the schists, and are mineralized with pyrite, chalcopyrite, sphalerite, arsenopyrite and tetrahedrite or tennantite in a gangue of quartz, dolomite, ankerite and sericite. The paragenesis follows:

1. Quartz—extensive initial silicification of the schist by dense, barren, almost chalcedonic quartz, later partly replaced by ankerite.
2. Sericitization (not extensive), chloritization (rich in iron) and carbonization.
3. Pyrite—replacing quartz as well as replaced by it.
4. Magnetite and specularite.
5. Arsenopyrite.
6. Sphalerite—locally quite abundant and occasionally containing later galena.
7. Chalcopyrite.
8. Tennantite.
9. Secondary minerals—calcite, abundant gypsum, chalcocite, cuprite.

Apart from being magmatic emanations, no definite igneous source is suggested for the mineralizing solutions.

Rio Tinto, Spain.[46]

The Sierra Morena Mts. in which these deposits are located, have been recently carved from a peneplain. This exposed the ore bodies to erosion, oxidation and secondary downward enrichment.

[45] Lindgren, W.: Ore Deposits of the Jerome and Bradshaw Mountains Quadrangles, Arizona. U. S. Geol. Surv. Bull. 782, 1926.

[46] Bateman, A. M.: Ore Deposits of the Rio Tinto (Huelva District), Spain. ECON. GEOL., vol. 22, pp. 569–614, 1927.

The rocks of the district are Culm (lower-Carboniferous) slates intruded by porphyries and diabase. The slates were involved in the lower Carboniferous-Permian folding and now dip steeply to the north. The intrusions are sills, themselves slightly sheared and intruded near the end of the folding.

The many ore deposits lie in shear zones in the slate or porphyry or at slate-porphyry or slate-diabase contacts as great lenses arranged en echelon. The deposits range in size up to 1700 × 250 metres, and attain a maximum depth of 550 m. They consist of nearly pure sulphides (chiefly pyrite) flanked by disseminated sulphides the whole enclosed by a sericite aureole. Besides the pyrite, small amounts of chalcopyrite, sphalerite, galena, arsenopyrite, tetrahedrite (all primary), secondary copper sulphides, iron oxides, Cu-Sb and Cu-As sulphides as well as some Ni-Co minerals occur.

Bateman concludes they are normal hydrothermal replacement deposits formed by aqueous solutions ascending from the same magmatic reservoir that yielded the intrusions following shear zones, and replacing the adjacent porphyry and slate with sulphides.

Hidden Creek Mine, Anyox, B.C.[47]

This mine, during the last few years, averaged around one and one-half million tons of ore per annum, yielding approximately 1.2 per cent. Cu, $0.06 in Au, and .17 oz. Ag per ton. The total production (the mine closed permanently during 1935) was around twenty-two million tons of ore. The deposit consists of six ore bodies, replacements in argillite, in greenstone or along their contact, consisting of pyrite and pyrrhotite with subordinate chalcopyrite and some blende in a silicified country rock. The argillites and greenstone, near the center part of a late Paleozoic and early Mesozoic roof pendant in the Coast Range granite batholith, which is 2000 feet from the deposit, are heavily silicified

[47] McConnell, R. G.: Geol. Sur. Can. Sum. Rept., 1913, pp. 55–57. Campbell, E. E.: The Hidden Creek Mine and its Operation. Can. Min. Inst. Trans., vol. 22, pp. 135–154, 1920. Bancroft, J. A.: Mine Report on the Geology and Ore Deposits of the Anyox Map Area (unpublished), 1920. Kania, J. E.: Ore Deposits of the Hidden Creek Mine, Anyox, B. C. (unpublished), 1927.

along their contact for a width of 200 to 400 feet. The greenstone or altered amphibolite, has a composition similar to andesite or fine-grained diorite, and, as a sill, is intrusive into the argillites. This intrusion was followed by that of the Coast Range granite batholith, which gave rise to the extensive initial silicification, most intense in the ore zone, followed by the sulphides. No contact metamorphic minerals occur. Chlorite, muscovite, and sericite are extensively developed in the mineralized area. The greenstones are most extensively silicified where they are schistose.

The paragenesis of the minerals follows: 1. Silica. 2. Pyrite. 3. Pyrrhotite. 4. Sphalerite. 5. Chalcopyrite. 6. Arsenopyrite (as small perfect crystals in pyrrhotite and chalcopyrite). 7. Calcite.

Practically solid bodies of pyrite contain much less copper than much of the disseminated ore. Pyrrhotite mostly forms the margins of the heavy sulphide bodies, the smaller isolated ones of which are essentially pyrrhotite throughout. At the expense of the pyrite, the pyrrhotite becomes increasingly more abundant with depth in some of the ore bodies. The low gold and silver values are persistent.

A short petrographic description of the argillite and greenstone may be of interest.

The Argillites.—These rocks are dense, fine-grained, dark gray. The individual beds vary from a fraction of an inch to 4 feet in thickness. They consist chiefly of quartz with minor amounts of feldspar, kaolin, sericite, carbonaceous matter, chlorite, calcite, magnetite, biotite, muscovite, tremolite, rutile, pyrrhotite and pyrite named in decreasing order of abundance. The micas, tremolite, rutile, and hornblende occur at the contacts with the intrusive porphyrite.

The Greenstones.—These are generally massive except in the ore zone near the intruded argillites where they are intensely foliated. They consist chiefly of fibrous green hornblende, plagioclase, chlorite, scattered magnetite and secondary quartz. Minor amounts of epidote, biotite, titanite, zoisite, calcite, leucoxene, pyrite and pyrrhotite also occur. In the schistose rock chlorite, quartz and actinolite become more plentiful.

Britannia Mine, Howe Sound, B.C.[48]

Four of the five ore bodies are replacements in green schist (the Britannia sills, quartz porphyry to diorite porphyrite in composition) along an irregular, steeply dipping schist-slate contact, and three of these four ore bodies are localized within re-entrant angles or wedges of the green schist in the slates. The latter form the hanging wall in two cases, the former in one case (the Empress). One ore body, the Jane, although near the contact, lies entirely within the slates (part of the Britannia formation). The deposits occur within an extensive shear zone. The gangue is almost entirely silicified quartz schist. As is the case with the Hidden Creek Mine the country rock here is part of a roof pendant, striking E-W, in the Coast Range batholith, which is held responsible for the mineralizing solutions and here has the composition of a biotite granodiorite.

The minerals found are pyrite, chalcopyrite, locally much sphalerite, rarely galena, in a silica gangue. Gypsum occurs in lenses 10–30 feet wide. It is gray white, has sharp contacts with the schist and near the edges contains long thin flakes of the schist in the original position. The gypsum shows no trace of shearing. Sulphur also occurs, but widely removed from the gypsum, as veins and impregnations in the schist. Small, colorless gypsum crystals are associated with the sulphur. Schofield does not think the sulphur was derived from the gypsum and postulates an origin for it genetically connected with the magma reservoir that gave rise to the Tertiary Garibaldi volcanic field six miles to the north.

Mount Lyell District, Tasmania.[49]

The four main mines in this district, which lies on the west coast of Tasmania, are the Mount Lyell, the North Mount Lyell, the South Tharsis and the Royal Tharsis.

[48] McConnell, R. G.: *Op. cit.*, pp. 76–79. Schofield, S. J.: Geol. Sur. Can. Sum. Rept. 1918, Pt. B, pp. 56–69; ECON. GEOL., vol. 21, pp. 271–284, 1926.

[49] Gregory, J. W.: The Mount Lyell Mining Field, Tasmania. Trans. Aust. Inst. Min. Eng., Melbourne, vol. 10, pp. 26–197, 1905. Gilbert, C. G., and Pogue, J. E.: The Mount Lyell Copper District of Tasmania. Proc. U. S. Nat. Mus., vol. 45, pp. 609–625, 1913.

The rocks of the district consist of a North-South belt of sericite schists supposedly dynamometamorphic forms of Paleozoic acid porphyries thrust faulted against conglomerate on the east and in contact with Silurian sediments on the west. The ore bodies, localized at the junction of cross faults with the main faults, form lenticular replacements in the schist along its eastern border. Considerable masses of "porphyrites" are intrusive into the schists.

The ore consists of fine grained pyrite in a gangue of quartz and minor amounts of: 1. Pyrite—slightly cupriferous. 2. Chalcopyrite—in increasing amounts as the pyrite decreased. 3. Bornite—intimately associated with chalcopyrite. 4. Enargite. 5. Tetrahedrite.

The increasing copper and decreasing iron content of the solutions during mineralization is stressed.

APPLICATION OF CONCLUSIONS TO THE DEPOSITS.

Since the experiments performed and described in the previous pages dealt only with silica, iron sulphide, iron copper sulphide and zinc sulphide solutions and sols, the conclusions derived will, in the main, find application only to the earlier although, from an economic standpoint, the most important phase of the mineralization period of the mesothermal pyritic copper deposits.

Whereas it was shown by experiment that Na_2S-SiO_2 solution coagulated FeS_2 sol, which in turn coagulated $CuFeS_2$ and ZnS sols, and whereas of the latter two, ZnS seems to lag slightly behind the $CuFeS_2$ in coagulation, the order of ascent of these substances from the magma, after having been extracted with magmatic water, is probably as follows, with the one that will stay longest in solution or suspension first: 1. Silica (barren). 2. Pyrite. 3. Chalcopyrite. 4. Sphalerite.

This is in accord with the paragenesis of the minerals as observed in ore specimens from these deposits. If the exception occurs, and silica is not extensively developed, as at Rio Tinto, then the magma responsible for the mineralization was probably poor in that substance or, as is more likely, the silica capping dis-

cussed below has been removed by erosion. The great majority of these deposits, however, can be genetically connected with silicious magmas (*e.g.* granites, acid porphyries, etc.) hence the extensive initial silicification barren of the metal sulphides. The Na_2S–SiO_2 water, then, charged with H_2S and CO_2 on reaching a zone of increased pressure gradient, such as a shear zone, which offers a relatively easy escape to the H_2S in the solution, would deposit their SiO_2 while the gases and the Na as the carbonate or bicarbonate would escape to the surface.

Regarding the Na_2S in the ascending CO_2 charged Na_2S–SiO_2 acid solutions, it is a reasonable assumption that it is carried up to the surface as the water-soluble Na_2CO_3 or rather as $NaHCO_3$ and dissipated. Certainly the laws of chemistry are satisfied with this process and there is no need for the Na to remain in the rocks as Na_2S as some writers indicate. Hence, not finding Na_2S in the rocks is no criterion that Na_2S did not play an important part in the mineralization. As it is so frequently a shear zone or a contact that is silicified, the ascending solutions would not be hampered by physical obstacles in disposing of the sodium carbonate. The next step in the mineralization would be, then, the ascent of CO_2 and H_2S charged Na_2S–FeS_2 solutions, into this silicified shear zone. On reaching this shear zone containing also possibly some calcareous rocks, the FeS_2 would be deposited (due to the escape of H_2S and the formation of Ca $(HCO_3)_2$ and the Na_2S, again as the carbonate or acid carbonate, carried off to the surface. All these solutions leaving the magma are acid, not alkaline, due to the presence of both CO_2 and H_2S.

These ore deposits are mostly found in a zone initially heavily silicified and as, by experiment, it was found that crystalline silica has no peptizing effect on double sulphides carried by waters charged with CO_2 and H_2S, there is no reason why these later solutions should not deposit their metallic load in this favorable zone of increased differential pressure, already sought out by the earlier solutions as a favorable locus for mineralization. The H_2S would be forced out of solution and it, as well as the excess of CO_2 and sodium carbonate or bicarbonate would be carried out to the surface.

It is striking how closely this theoretical aqueous magmatic emanation parallels the sodium bicarbonate waters as observed in nature. To quote W. Lindgren: [50]

> The characteristic sodium carbonate waters are . . . of deep-seated origin and usually break through the older igneous or metamorphic rock underlying the lavas in regions where the active volcanism has ceased; the prevailing opinion is that the waters with their charge are in whole or in part of magmatic origin. They rarely contain much calcium and they are poor in silica, but are usually heavily charged with carbon-dioxide and sometimes hydrogen sulphide.

As the ascending Na_2S–FeS_2 solutions reach the silicified zone the silica is leached (shown by experiment) the FeS_2 deposited (also shown by experiment) and the leached SiO_2 carried away from the metal sulphide and redeposited.[51]

Theoretically, then, above a pyrite ore body say, there should be a capping of second generation silica which was leached from the space now occupied by the sulphides, carried (mainly) upwards by the ascending magmatic waters and redeposited (generally away from the sulphide).

The silica and pyrite having been extracted from the magmatic chamber responsible for this particular ore body, the sphalerite and chalcopyrite are able to follow next, also as double sulphides with sodium, penetrate the ore body and replace the silica and pyrite which are carried further along and redeposited. The above theoretical mineralization, although not complete, worked out on the basis of experiments, finds its counterpart in the mesothermal pyritic copper deposits a few of which have been described for illustrative purposes.

The importance of the rôle of Na_2S in the formation of this type of ore deposit and probably others as well, is often questioned. The chemistry of the mineralization process is sound and its theoretical geological application based on a large number of experiments, was found to be in agreement with facts as they are observed in connection with these deposits.

[50] Mineral Deposits, 1928, p. 63.

[51] Note: No data are at hand to show whether or not FeS_2 peptizes SiO_2 though it was shown by experiment that SiO_2 coagulated FeS_2. The reverse is possibly true.

SUMMARY.

With a view to determining whether or not colloids in the rôle of double sulphide solutions and sols of Na_2S with the heavy metal sulphides as well as Na_2S combined with SiO_2, would be able to account for the type of mineralization characteristic of the mesothermal pyritic copper deposits, the problem was attacked experimentally.

First, the literature was reviewed and the relevant data on the behavior and stability of colloidal solutions as well as the formation of crystals from them chronologically summarized.

Then a number of melts were prepared, mixing in molecular proportions fused powdered Na_2S with powdered pyrite, chalcopyrite, sphalerite, galena and silica respectively. The cooled melts were finely crushed, extracted with distilled water, filtered and the filtrate used in the experiments, some 230 of which were performed.

The behavior of these solutions (varying the concentrations) was observed at 25° C., 32° C., 95° C. and cooled to 32° C., and at 90° C. continuously, in contact with various rocks such as marble, lime mud-rock, syenite porphyry, argillaceous quartzite and carbonaceous shale, and with or without CO_2 and (or) H_2S gas. Although the formation of crystals was not the main object of this paper, which deals mainly with the stability of the sols and solutions in various environments, pyrite, marcasite and chalcopyrite crystals formed in some of the tubes. Marcasite formed from FeS_2 sols with very little Na_2S present (neutral or acid, cold or hot). Pyrite from Na_2S–FeS_2 solutions under similar conditions, as well as in alkaline solutions and chalcopyrite from a hot alkaline sol as replacement in crystalline limestone.

The solutions and sols prepared with hot water were found to be more stable at lower temperatures than those prepared with cold water. Calcium bicarbonate was found to be the most powerful coagulant in all the experiments performed, especially if H_2S had an opportunity to escape which it does mainly due to the presence of excess CO_2.

It was found that Na_2S–SiO_2 solution coagulated FeS_2 sol, which in turn coagulated $CuFeS_2$ and ZnS sols. From this it was

reasoned that the most easily soluble or suspended substance ascended first from the magma chamber, the order therefore being: 1. Silica. 2. Pyrite. 3. Sphalerite and chalcopyrite.

It is postulated that the Na_2S in combination with these substances is carried off to the surface, along with CO_2 and H_2S, as the carbonate and acid carbonate, which is also a reason for thinking that these solutions, due to the presence of excess CO_2, are acid throughout the mineralizing process, and not alkaline.

Some type deposits of the mesothermal, pyritic copper deposits are described, a theoretical mineralization process as worked out from the experiments applied to them, and the theoretical result compared with facts known regarding these deposits, a close parallel being established in all instances.

Problems Still to be Solved.

A whole series of future investigations has been opened up by the promising results derived from the experimental work described in these pages. Some of the problems still to be solved are enumerated below.

1. Substitute K_2S for Na_2S in these or similar experiments and note the results and rock alteration (sericitization?).

2. The conditions under which the sulphides will crystallize from double sulphide solutions and sols, so that the process can be duplicated at will.

3. A more extensive investigation of the conditions that determine whether pyrite or marcasite shall crystallize from an FeS_2 solution or sol.

4. An investigation into the barite, gypsum and anhydrite mineralization, characteristic of these deposits, in an experimental way, to determine whether or not colloidal solutions would give an explanation of this phase of the subject.

5. Investigating the relations between pore space, differential pressure and sulphide sols and solutions to determine the importance of pore space in rocks in the localization of ore deposits.

VANCOUVER, B. C.,
CANADA,
March 25, 1936.

THE GREENSANDS OF WISCONSIN.

W. H. TWENHOFEL.

INTRODUCTION.

THE greensands of Wisconsin are confined to strata of the Upper Cambrian (Croixian Series) in which they are largely limited to a single formation. The same strata are also exposed in eastern Minnesota and northeastern Iowa and deep wells show extensions in these states westward of the exposures and southward from Wisconsin into Illinois.

The field studies on which this paper is based were initially supported by the Wisconsin Geological and Natural History Survey, at first under the direction of W. O. Hotchkiss and later under E. F. Bean, the support being for work to which the studies on the greensands were mainly incidental. Later field studies were carried on by personal funds except that some information was acquired in connection with work supported by a grant from the Penrose Bequest of the Geological Society of America. The paper directs attention to the distribution and variations of the greensands and their possible utilization in agriculture.

GEOLOGIC SECTION OF THE GREENSAND-CONTAINING STRATA.

The greensands, the name being due to the presence of greater or less quantities of the green mineral, glauconite, a hydrous potassium silicate, are largely confined to the Franconia formation, but minor occurrences are present in two other formations.

The geologic section that follows gives the setting of the formations concerned.

Ordovician
  Oneota dolomite

Cambrian
- Trempealeau formation
  - Madison-Jordan sandstone member
  - Lodi shale member
  - St. Lawrence dolomite member
  - Basal conglomerate and greensand member
- Franconia formation
  - Bad Axe sandstone member
  - Hudson sandstone member
  - Goodenough sandstone member
  - Ironton sandstone member
- Dresbach formation
  - Galesville sandstone member
  - Eau Claire sandstone member
  - Mt. Simon sandstone member

The greensands are largely confined to the Bad Axe and Goodenough members, but it should be noted that these members are not everywhere conspicuously filled with greensand and, on the other hand, there is locally some greensand in the basal part of the Trempealeau formation and the Eau Claire member of the Dresbach formation contains small quantities. Details of the formations other than the Franconia [1] are not given in this paper as such have little or no bearing on the present objectives.

FRANCONIA FORMATION.

The Franconia formation exhibits much lateral variation in both the general lithology and the content of greensand. There are areas and horizons where the content is negligible and in many parts of the state the four divisional arrangement given above is impossible or is made with difficulty.

The Ironton member is composed of more or less poorly sorted and comparatively coarse-grained sands in the lower part, and better sorted and finer-grained sands toward the top. Many of the beds are much borrowed by organisms and some glauconite

[1] For details of the Cambrian section see "Cambrian strata of Wisconsin," by Twenhofel, Raasch and Thwaites: Bull. Geol. Soc. Am., vol. 46, pp. 1687–1744, 1935.

seems to be invariably present, but the quantity generally is small. The thickness ranges from 3 to 15 feet or more.

The Goodenough member has three units which in ascending order are the Calcareous, Micaceous Shales, and Lower Greensand, but these units are not everywhere differentiable. In places the horizon of the Calcareous unit is a glauconitic limestone, but more commonly it is a sandstone with a calcareous cement. The thickness ranges to about 4 feet. The Micaceous Shale is a rather evenly and thin-bedded, micaceous, fine-grained sandstone or a siltstone. It contains no clay. The color is gray to pale yellow. The quantity of glauconite usually is small, but a little is generally present. The maximum thickness is about 15 feet.

The Lower Greensand, where typically developed, consists of horizontally and cross-laminated glauconitic sandstones interbedded with non-laminated glauconitic sandstones that are irregularly mottled with areas of blue, blue-green, and yellow silts or fine-grained sandstones. These non-laminated beds contain many organic burrows and it seems obvious that the materials made one or more passages through the intestinal tracts of organisms. Some beds are mud cracked. The Lower Greensand is perhaps the most glauconitic part of the Franconia formation and some beds are extremely rich in the mineral. Data in this respect are given on later pages. The thickness ranges to around 40 feet.

The Hudson member consists of more or less flour-like, fine-grained, poorly cemented, yellow sandstones which in some parts of Wisconsin are without glauconite, but in other parts contain more or less minor quantities of the mineral. The thickness ranges to 50 feet.

The Bad Axe member includes what formerly was known as the Upper Greensand. The strata consist of friable sandstones which locally contain considerable glauconite and some beds are rich in the mineral. On the other hand, the strata are not everywhere conspicuously glauconitic. The thickness ranges from 20 to 50 feet.

As previously stated the Trempealeau formation contains

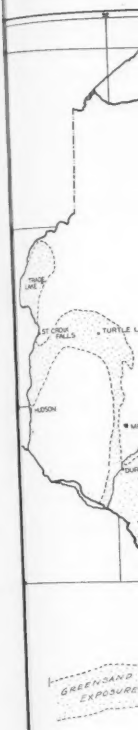

FIG.
sin.
St. C
known
Ripon
to be

FIG. 1. Shows approximate distribution of the greensands of Wisconsin. Considerable distribution may be found along the Mississippi and St. Croix rivers in the adjacent parts of Iowa and Minnesota. Little is known respecting exposures in the eastern part of Wisconsin north of Ripon, but the quantity of glauconite in the greensand strata is thought to be rather small.

glauconite in the basal conglomerate and in the St. Lawrence dolomite, but the quantities are ordinarily too small for consideration as a source for the mineral. The association of the glauconite and carbonate in the St. Lawrence member, however, may enhance the agricultural value of that rock because of the common presence of both lime and potash. Minor quantities of glauconite, in the form of very small particles, are present in some beds of the Eau Claire member. The map (Fig. 1) gives the general distribution of the Franconia formation.

Detailed Description of Some Sections of the Franconia Formation.

Several sections of the Franconia formation from west to east will serve to give details. Each section is given in descending order. Unless otherwise stated, the sandstones have quartz as the most important mineral. The glauconitic content was determined by means of an electro-magnet and the given percentages are slightly higher than the actual content of glauconite because of the adherence of quartz particles to the glauconite grains.

Section at Grandfather Bluff, La Crosse, Wisconsin.

15. Greensand, poorly exposed, lower part of Bad Axe member 17 feet
14. Covered slope with glauconitic sandstones exposed in road ditch ..... 61 feet
13. Sandstone, yellow, shaly, glauconitic in some layers ..... 20 feet
12. Greensand with thin laminations of yellow shale, range of glauconite from 88 to 93 per cent. ..... 0.2 foot
11. Sandstone, glauconitic, fine-grained, mottled green and gray 2 feet
10. Greensand, very rich in glauconite, contains lenses of hard yellow sandstone to one half inch thick ..... 0.12 foot
9. Sandstone, fine-grained, yellow, thin-bedded, contains light-colored mica ..... 3 feet
8. Greensand, interbedded with light-yellow sandstone, lower 2 inches very rich in glauconite ..... 0.5 foot
7. Sandstone, shaly, micaceous, no glauconite ..... 1.25 feet
6. Limestone, little or no sand, flecked withh glauconite, beds 2 to 12 inches ..... 2.5 feet
5. Sandstone, fine-grained, yellow, some lenticular laminations contain much glauconite ..... 1.10 feet

4. Limestone, interlaminated with cross-laminated greensand and yellow sandstone. Every bed contains some carbonate and the limestone contains some quartz sand .... 1.5 feet
3. Greensand and yellow sandstone, contains many burrows filled with fine-grained yellow sands. Rich in glauconite 1 foot
2. Sandstone, cemented with fine-grained sandy materials containing iron oxide and carbonate ..... 0.25 foot
1. Sandstone, yellow, interlaminated with greensand. Base of Franconia ..... 0.72 foot

Norwalk Hill Section, Norwalk, Wisconsin.

11. Sandstone, very fine-grained, very calcareous in some layers. Contains glauconite more or less throughout and a 16–18 inch layer about 2 feet from the base has it in considerable quantity. Top of Franconia formation, Upper Greensand, or Bad Axe member ..... 27 feet
10. Greensand and yellow sandstone, both fine grained ..... 8 feet
9. Sandstone, gray to yellow, fine-grained, not very glauconitic 40 feet
8. Sandstone and greensand, former gray ..... 3 feet
7. Greensand, very rich in glauconite, really a lens ..... 1.6 feet
6. Greensand, thin-laminated, not rich in glauconite ..... 3.5 feet
5. Greensand, very rich in glauconite ..... 0.9 foot
4. Sandstone, gray, flecked with glauconite ..... 1.5 feet
3. Sandstone and greensand, former gray ..... 0.9 foot
2. Greensand, thick-bedded, mud cracked layer near top .... 11 feet
1. Sandstone, yellow, fine-grained, flakes of white mica on bedding planes. Contains 1–2 per cent. glauconite .... 20 feet

Tunnel City Section, Tunnel City, Wisconsin.

This section is exposed on the eastern portal of the tunnel on the Chicago and Northwestern Railroad at Tunnel City, a small place between Tomah and Sparta. The section represents the Franconia from the Ironton to the lower part of the Lower Greensand.

3. Greensand, alternations of yellow and gray sandstone with greensand ..... 18 feet
2. Greensand, brown to yellow, thin-laminated, glauconite present but not abundant ..... 14.5 feet
1. Sandstone, fine-grained, thin-laminated, beds ½–6 inches, no glauconite, belongs to Galesville member of Dresbach formation ..... 14 feet

Details of zones 2 and 3 are as follows (Evan Thompson, unpublished thesis, University of Wisconsin, 1920):

16.	Sandstone, shaly, contains a little glauconite	1.5 feet
15.	Sandstone, yellow, and greensand interlaminated, contains about 10 per cent. glauconite	1.5 feet
14.	Greensand, about 20 per cent. glauconite	0.75 foot
13.	Sandstone, yellow, thin-laminated, averages 5.7 per cent. glauconite	0.66 foot
12.	Sandstone, yellow, contains 4.3 per cent. glauconite	0.40 foot
11.	Greensand, 67 per cent. glauconite	0.01 foot
10.	Sandstone, yellow	0.25 foot
9.	Greensand	0.16 foot
8.	Sandstone, yellow, shaly, 5 inches from bottom a 2-inch layer with 10 per cent. glauconite	1.66 feet
7.	Greensand, contains 24.67 per cent. glauconite	0.66 foot
6.	Greensand, interlaminated with yellow sandstone	0.33 foot
5.	Greensand, shaly, 10 per cent. glauconite	2.00 feet
4.	Greensand, 21.49 per cent. glauconite	0.50 foot
3.	Sandstone, yellow and speckled with glauconite	0.50 foot
2.	Not exposed	4.00 feet
1.	Sandstone, yellow to greenish-yellow, 13.3 per cent. glauconite	18.00 feet

Boscobel Section, Boscobel, Wisconsin.

This section is exposed on the north side of the Wisconsin River, opposite the town of Boscobel, and it represents the Upper Greensand or Bad Axe member. The exposures consist of interlaminated greensand and yellow sandstone. The glauconite content for the entire 15 feet approximates 20 per cent. The glauconite content for different parts is as follows:

Basal two feet	23 per cent. glauconite
Third foot	18 per cent. glauconite
Fifth and sixth feet	22 per cent. glauconite
Seventh and eighth feet	30 per cent. glauconite
Twelfth and thirteenth feet	17.7 per cent. glauconite

Maple Bluff Section, Madison, Wisconsin.

This section represents the upper part of the Franconia formation and is exposed in Maple Bluff on the north shore of Lake Mendota. The section was carefully studied by Clyde Dickenson in 1923–24 (unpublished thesis, University of Wisconsin, 1924). The details are as follows:

26. Sandstone, greenish yellow, 21.5 per cent. glauconite ..... 0.8 foot
25. Sandstone, greenish yellow, 15 per cent. glauconite ..... 2.5 feet
24. Sandstone, greenish white, 35 per cent. glauconite ..... 1.3 feet
23. Sandstone, greenish yellow, 16 per cent. glauconite ..... 0.4 foot
22. Sandstone, greenish white, 23 per cent. glauconite ..... 0.4 foot
21. Sandstone, greenish white, 15 per cent. glauconite ..... 0.9 foot
20. Sandstone, greenish white, 18 per cent. glauconite ..... 0.5 foot
19. Sandstone, brownish green, 15 per cent. glauconite ..... 2.0 feet
18. Sandstone, greenish white, 12.5 per cent. glauconite ..... 3.3 feet
17. Sandstone, greenish white, 14 per cent. glauconite ..... 0.8 foot
16. Sandstone, greenish white, 24 per cent. glauconite ..... 0.5 foot
15. Sandstone, yellow, 11 per cent. glauconite ..... 0.9 foot
14. Sandstone, white, 15 per cent. glauconite ..... 0.3 foot
13. Sandstone, yellow, 8 per cent. glauconite ..... 0.5 foot
12. Sandstone, white, 14 per cent. glauconite ..... 0.5 foot
11. Sandstone, yellow, 9 per cent. glauconite ..... 2.0 feet
10. Sandstone, white, 8 per cent. glauconite ..... 2.7 feet
9. Sandstone, yellow, 10 per cent. glauconite ..... 0.8 foot
8. Sandstone, white, 12 per cent. glauconite ..... 1.2 feet
7. Sandstone, white, 8 per cent. glauconite ..... 1.0 foot
6. Sandstone, yellow, 4 per cent. glauconite ..... 3.0 feet
5. Sandstone, white, 6 per cent. glauconite ..... 7.4 feet
4. Sandstone, yellow, dolomitic, a little glauconite ..... 1.3 feet
3. Sandstone, white, 1.5 per cent. glauconite ..... 4.0 feet
2. Sandstone, white, trace of glauconite ..... 2.0 feet
1. Sandstone, yellow, 0.7 per cent. glauconite ..... 3.9 feet

General Characteristics.

The greensand strata present much variation from place to place and also in vertical section. Many units are not defined by well marked bedding planes, are not continuous, and thicken and thin to a marked extent with the change in thickness generally rather gradual. About half of the beds are thin-laminated with the lamination planes ranging from essential parallelism to the larger bedding planes to low angles thereto. Inclinations of the cross-lamination are rarely high, but directions of inclination vary widely. Many beds are without lamination planes of any kind. These beds contain numerous organic burrows to which the absence of lamination is due. The repeated occurrence of such beds is taken to indicate slow deposition of the entire Franconia

formation except the basal strata and perhaps an occasional bed at other levels in the section. The low angles of most of the cross-lamination and the abundance of glauconite are also evidence of slow deposition.

The strata of the Franconia formation were deposited under marine conditions as is proven by the general occurrence of marine fossils. Most of the fossils seem to have undergone some transportation before final entombment. Entire specimens of trilobites are extremely rare, but complete inarticulate brachiopods are common and some beds have many entire protremate brachiopods. The waters were never deep, but do not seem to have been affected by very violent wave activity and it is probable that the waters were too shallow to permit large waves to form. Extreme shallowness and occasional times of exposure above water are proven by the mud cracks present in parts of the formation. The sands are generally well sorted and dimensions of particles range for most beds between 1/16 and 1/2 mm.

The glauconite content of the greensands varies greatly from bed to bed; likewise the content varies laterally in each bed. The content of glauconite in greensands of the northeastern part of the state is small compared to that in the central and western parts.

Description of the Glauconite.

The greensand or glauconite particles are rarely spherical, but most particles have the surfaces curved. A few are subangular. In general, the shapes may be described as irregularly round. Many have mammillary surfaces and it is thought that such surfaces are connected with their origin. Parts of the surfaces of most particles appear as if polished and reflect light when observed through a microscope. Many surfaces have depressions caused by impingement of the associated quartz grains.

The dimensions of the glauconite particles range from microscopic to about 1/2 mm. in diameter, the general range being from about 1/16th to 1/2 mm. There are few larger than 1/2 mm. The particles of largest dimension in the Lower Greensand of

the Norwalk section approximates 3/8 mm. Particles from the Upper Greensand of the same section are of similar dimension but seem to contain many ellipsoidal particles of which the longest diameters approximate 1/2 mm. It is thought that the particles of dust dimension may represent material abraded from larger particles, that some of the particles of intermediate dimension may have acquired such dimension because of abrasion, and that the particles with great spherical irregularity are those little abraded and hence nearest the original shapes.

Chemical Composition of Glauconite.

Analyses of glauconite show wide variation. This may be due to imperfections of concentration, to faulty analysis, and also to the probability that glauconite does not have a definite composition. Clarke [2] suggests that the formula for pure glauconite is F''' $KSi_2O_6.nH_2O$ and states that some of the iron may be replaced by aluminum and that other bases may replace the potassium. According to two analyses made by Caspari [3] the formula is $KFeSi_2O_6$. Hallimond [4] suggested the formula $R_2O.R_2O_3.RO.10SiO_2.nH_2O$; R_2O representing the alkalies, R_2O_3 the ferric iron and alumina, and RO the manganese. Schneider's study developed the formula (K.Na) (Fe.Mg) (Fe.Al) $Si_6O_{18}.3H_2O$. Schneider's [5] analyses (Nos. 1–3) are given below. As great care was taken in making the concentrates these represent essentially pure glauconite. In the preparation of the material for analysis the rock specimens were crushed and the glauconite separated by means of a powerful electro-magnet, the separation being repeated several times. The final concentrate contained 90 to 95 per cent. glauconite. The concentrates were then washed, dried, and hand picked under a binocular microscope, thus giving a concentrate of essentially pure glauconite.

[2] Clarke, F. W.: Data of geochemistry. U. S. Geol. Surv. Bull. 770, pp. 519–522, 1924.

[3] Caspari, W. A.: Proc. Roy. Soc. Edinburgh, vol. 30, pp. 364–372, 1910.

[4] Hallimond, A. F.: Min. Mag., vol. 19, pp. 330–337, 1922.

[5] Schneider, H.: A study of glauconite. Jour. Geol., vol. 35, pp. 289–310, 1927, and Ph.D. thesis, Univ. of Wis., 1926.

Ross expressed the view that glauconite is made up of two end members, of which one has the composition $R_2O : RO : R_2O_3 : SiO_2$ in the ratio of 1 : 2 : 2 : 10 and the other of $R_2O : RO : R_2O_3 : SiO_2$ in the ratio of 1 : 1 : 3 : 10; R_2O representing K_2O and Na_2O, RO magnesia and ferrous iron and R_2O_3 alumina and ferric iron. As thus worked out Ross considered the facts as best interpreted by considering glauconite an isomorphous mixture of the two end members with formulas of $2H_2O.K_2O.2(MgO, FeO).2(Fe_2O_3, Al_2O_3).10SiO_2.3H_2O$. and $2H_2O.(MgO, FeO).3(Fe_2O_3, Al_2O_3).10SiO_2.3H_2O$. It will be noted that the two formulae are not greatly different. Ross [6] states that the water of glauconite is partly water of crystallization and partly absorbed water, the $2H_2O$ seeming to be the quantity assigned to the latter. Galliher [7] seems to have shown that glauconite is an alteration product of biotite and that its composition depends upon the original composition of the biotite.

According to Schneider the alumina (Al_2O_3) content ranges to 10 per cent. and commonly is in excess of 7 per cent. It is interchangeable with the ferric iron (Fe_2O_3) and occasionally may be entirely replaced by it. Soda (Na_2O) is usually present in quantities less than 2 per cent., but occasionally it may equal the potash (K_2O). The sum of the magnesia (MgO) and ferrous iron (FeO) commonly is near 7 per cent. with each present in about equal quantity. These relations hold for the recent as well as the ancient glauconites and there is no increase in the potash content in the glauconites in the older portions of the geologic column although that statement has frequently been made.

Typical analyses of glauconite from Wisconsin are as follows:

The analyses show that the potash content of pure glauconite, estimated as K_2O, is of the order of magnitude of 7 per cent. so that the quantity in a greensand averaging 25 per cent. glauconite would be less than 2 per cent.

[6] Ross, C. S.: The optical properties and chemical constitution of glauconite. Proc. U. S. Nat. Mus., vol. 69, pp. 1–15, 1926.

[7] Galliher, E. W.: Glauconite genesis. Bull. Geol. Soc. Am., vol. 46, pp. 1351–1366, 1935; Geology of glauconite. Bull. Am. Assoc. Pet. Geol., vol. 19, pp. 1569–1601, 1935.

	1	2	3	4	5
SiO_2	49.00	48.50	49.40	45.91	49.12
Al_2O_3	9.20	9.00	10.20	11.47	7.09
Fe_2O_3	19.50	20.00	18.00	21.90	25.95
FeO	3.30	3.10	3.10	3.97	0.89
MgO	3.60	3.70	3.50	3.07	3.10
CaO	0.50	0.40	0.60	0.81	.....
Na_2O	0.90	1.50	1.40	trace	.....
K_2O	6.30	6.10	5.10	7.29	7.02
Loss on ignition	7.50	7.30	8.10	5.18	7.12
	99.80	99.60	99.40	99.60	100.29

1. Concentrate of glauconite from Hornerstown Marl, Cretaceous, Woodston, New Jersey. Concentrated by Schneider, analyzed by Brighton.

2. Concentrate of glauconite from Upper Greensand, Norwalk, Wisconsin. Concentrated by Schneider, analyzed by Brighton.

3. Concentrate of glauconite from base of Trempealeau formation, northwest of Norwalk, Wisconsin; concentrate by Schneider, analysis by Brighton.

4. Concentrate of glauconite from Franconia formation, Maple Bluff, near Madison, Wisconsin. Concentrated and analyzed by Clyde Dickenson. This was not concentrated so carefully as in the work of Schneider.

5. Modern glauconite from Pacific Ocean, off Panama, 556 fathoms. Analysis by Caspari. First treated with dilute HCl, followed by treatment with HCl and caustic soda and glauconite brought into colloidal suspension. This was coagulated and precipitated and later analyzed.

UTILIZATION OF THE WISCONSIN GREENSANDS.

It is not believed that the quantity of glauconite in the Wisconsin Greensands is present in thick beds in sufficient quantity to make these deposits of importance for the commercial extraction of the potash. Although some beds are locally rich in glauconite, these are mostly too thin for commercial utilization. The dimensions of the glauconite particles coupled with the quantity present does not favor its direct use for water softening purposes. However, there remains a probable future for local use of the deposits as fertilizer.

The potash in glauconite is only slightly soluble in water, but experiments by True and Geise [8] of the Bureau of Plant Industry have shown that in the early growing stages plants will take potash from greensand as effectively as from ordinary commercial potash. It was found that the greensands of New Jersey

[8] True, R. H., and Geise, F. W.: Experiments on the value of greensand as a source of potassium for plant culture. Jour. Agr. Research, vol. 15, pp. 483–492 1918.

and Virginia can supply the potash necessary for Turkey red wheat and red clover during the first two months of their growth and that they make a greater dry weight of tops than had been seen in similar cultures in which the potassium was acquired from potassium chloride, potassium sulphate, and potassium phosphate. McCall and Smith [9] of the Maryland Experiment Station state that the potash of greensand is rendered more available by composting the greensand with sulphur and manure and that without these substances the greensand yields little soluble potash. The New Jersey Agricultural Experiment station showed that the use of greensand in cultures produced increases in several crops,[10] and Shreiber [11] showed that soils containing glauconite require less potash in the form of fertilizers to give maximum yields than do soils without glauconite. Frapps [12] of the Texas Experiment Station obtained similar results. The work, in general, thus shows that treatment of soils with greensand gives positive results.

In order to learn the influence of the Wisconsin greensands on plant growth, the co-operation of Professor E. Truog of the College of Agriculture of the University of Wisconsin was enlisted. The research was assigned to Mr. H. J. Brant and pot culture investigations were undertaken. The greensand was derived from the Lower Greensand of the Norwalk section, east of Hudson, in St. Croix County, and from a locality in Monroe County, all within the greensand belt of western Wisconsin. The potash content of the glauconites used, not well concentrated, ranges from 3.54 to 5.57 per cent. The soil media for the cultures consisted of quartz sands and acid peat deficient in potash. A nu-

[9] McCall, A. G., and Smith, A. M.: Effect of manure-sulphur compost upon the availability of the potassium of greensand. Jour. Agr. Research, vol. 19, pp. 239–256, 1920.

[10] Greensand marl as a source of potash. N. J. Agr. College, Bull. 30, N. J. Agr. College Exper. Sta. Rept., pp. 358–368, 1917.

[11] Shreiber, C.: Glauconite as a fertilizer. Bull. Agr., Brussels, U. S. Exper. Sta. Rec., vol. 19, p. 725, 1907.

[12] Frapps, G. S.: Active potash of soil and its relation to pot experiments. Texas Exper. Sta. Rec., Bull. 145, p. 37, 1910; U. S. Exper. Sta. Rec., vol. 27, p. 323. 1912.

trient solution without potassium was used for all the cultures as follows:

Calcium nitrate	70 grams
Magnesium sulphate	26 grams
Calcium acid phosphate	13 grams
Ferric chloride	a pinch
Distilled water	20 liters

Thirty-six jars were used, of which twenty-four were filled with quartz sand, 12 Kg. to a jar, and twelve with peat, 2 Kg. to a jar. Glauconite was added at the rate of 12 gr. to a jar, corresponding to 1½ tons per acre. The test plants were corn and buckwheat. The corn and buckwheat on the quartz sands with glauconite were planted on March 20, 1920, and on April 9 in the peat. When about 2 inches high the corn was thinned to the two best plants to a jar and the buckwheat to about twenty plants to a jar.

The corn on the quartz sands with glauconite during the first few weeks showed no greater growth than the controls, but by the end of the fourth week the plants in the control had ceased to grow and the beneficial effects of the glauconite became marked except in the case of the glauconite derived from Monroe County in which the plants were no larger than in the cultures without glauconite. The plants on the quartz sands with glauconite were not as large as those in a pot that had received potash in the form of one gram potassium chloride added to the nutrient solution.

The buckwheat in the pots containing quartz sands with glauconite showed the beneficial effects of the glauconite much earlier than did the corn and greatly surpassed the growth made by the buckwheat in the pots without glauconite, but again the growth was inferior to that made in a pot to which the nutrient solution containing potassium chloride had been added.

The buckwheat on the peat with glauconite did not show a difference in growth between the controls and the peat-glauconite mixture until a later date than was the case for the pots containing the quartz sands. On the other hand the corn on the peat-glauconite mixture very early showed the influence of the glau-

conite and in all cases growth on the glauconite surpassed the growth on the controls.

The corn and buckwheat on the quartz sands with glauconite were harvested 70 days after planting, at which time growth seemed to have been accomplished. The corn grown on the quartz sands containing glauconite from Norwalk gave a dry weight about one and one-half times that grown on the sand without glauconite. The dry weight of the corn grown on the quartz-glauconite sands from the Hudson locality was a little greater than that grown on the check, and a little less for that from Monroe County. The corn grown with the soluble potash culture had a dry weight of nearly three times the check culture. The dry weight of the buckwheat grown on the quartz sands and Norwalk glauconite was nearly five times that of the check culture, the Hudson glauconite mixture gave a dry weight about three and a half times that of the check culture, and that of the Monroe County glauconite was two and seven-tenths that of the check culture. The growth on the soluble potash culture was six and four-tenths times that of the check. The plants grown on the peat cultures were harvested 55 days after planting and the results harmonized with those of plants grown on the quartz-glauconite sands except that the dry weights of the plants grown on the quartz sands with Norwalk glauconites were quantitatively similar to those of the plants grown on the soluble potash cultures.

The general conclusion derived from these studies is that the potash in some of Wisconsin greensands seems to be more readily available to plants than in others, that the results are different with different plants, that the best results are obtained when applied to peaty soils, and that some beneficial results are invariable.

It thus seems that the Wisconsin glauconite deposits should serve as local sources for potash fertilizer. Although not as beneficial as commercial potash, they nevertheless accelerate the growth of crops and increase the yield. Furthermore, they would generally cost nothing more than the labor of shoveling from a bank and the haulage. They should serve the regions of outcrop and adjacent areas as local sources of potash. No money

outlay is required other than wear and tear on tools of excavation and the vehicles of load transportation.

Those desiring to utilize the glauconite deposits should find exposures where the overburden is not excessive, where the formation is not well cemented, and where the color is some shade of green due to the abundance of the glauconitic particles. Thus, such a deposit is that at Norwalk, that on the highway in Minnesota extending south from St. Croix Falls in its ascent from the river valley, and that at Boscobel. Numerous other places are readily available. It is probable that the Wisconsin Geological and Natural History Survey would assist communities in locating deposits suitable for working.

UNIVERSITY OF WISCONSIN,
MADISON, WISCONSIN,
April 15, 1936.

ORE DEPOSITION SOUTH OF OURAY, COLORADO.

PART II.

ROBERT S. MOEHLMAN.

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CRITICAL PERMEABILITY.

The order of deposition of minerals in the San Juan region will be discussed in the following pages. During mineralization, valueless minerals may be deposited during one period and valuable ores during another; but if a fissure was not accessible to mineralizing solutions *at the time* valuable minerals were being deposited, it must be barren. A fissure may have been inaccessible because it was formed later than the period of ore mineralization, or because it became filled by worthless minerals before deposition of the valuable minerals.

If early barren or late barren minerals occur along a fissure, with no sign that valuable minerals have been introduced, prospecting along it is a dubious undertaking. On the other hand, if valuable minerals are present in minor amount in a fissure, indicating that the fissure did serve as a channelway at the time valuable minerals were precipitated, the vein may be quite profitable, given the proper conditions of structure, wall rock, and depth. Ore shoots occur where flow of mineralizing solutions

was concentrated at the time of deposition of the valuable minerals.

DISCUSSION: FORMATION OF A VEIN.

The ores of the western San Juan mining region are often regarded as type examples of open space filling. The present microscopic examination of ore and gangue minerals, however, clearly demonstrates that replacement was a much more important process in the formation of the veins of the western San Juan region than has been generally recognized. There was replacement, not only of wall rock but of previous vein material, as shown by preservation of "ghosts" of wall-rock texture and of the structure of pre-existing vein minerals, and by corroded borders of minerals. A brief criticism may be given of some of the criteria used to determine the manner and order of mineral deposition.

1. Vugs and open spaces in a vein do not prove that the whole vein was formed by filling of an open fissure. Replacement occurs not because of constricted space, but rather because reaction with previously formed minerals may cause deposition from solution when mere cooling will not. Replacement and deposition in open space are not mutually exclusive; it is possible that some minerals form by replacement, while others are being deposited in open space. Moreover, replacement on an important scale requires a channelway to dispose of the replaced material. The last stage of mineralization observed in all the ores of the western San Juan district is the deposition of quartz in open vugs. But this does not prove that the minerals encrusted by this late quartz were formed entirely by open-space filling.

2. The presence of well-formed crystals does not necessitate open space. Some minerals have a strong crystallizing power, developing crystal form even under adverse conditions. In the San Juan ores, pyrite, specularite and arsenopyrite were observed to form crystals whether developing by replacement or growing in open space. Quartz may form euhedral crystals when replacing a weak host like carbonate or barite. Some minerals, however, were not observed to have developed crystal boundaries and presumably need open space or some very weak host to develop crystals. These minerals of low crystallizing power are: galena, sphalerite, tennantite, and gold.

3. Since replacement is selective, positional association of minerals depends on chemical relations as much as or more than on closeness in

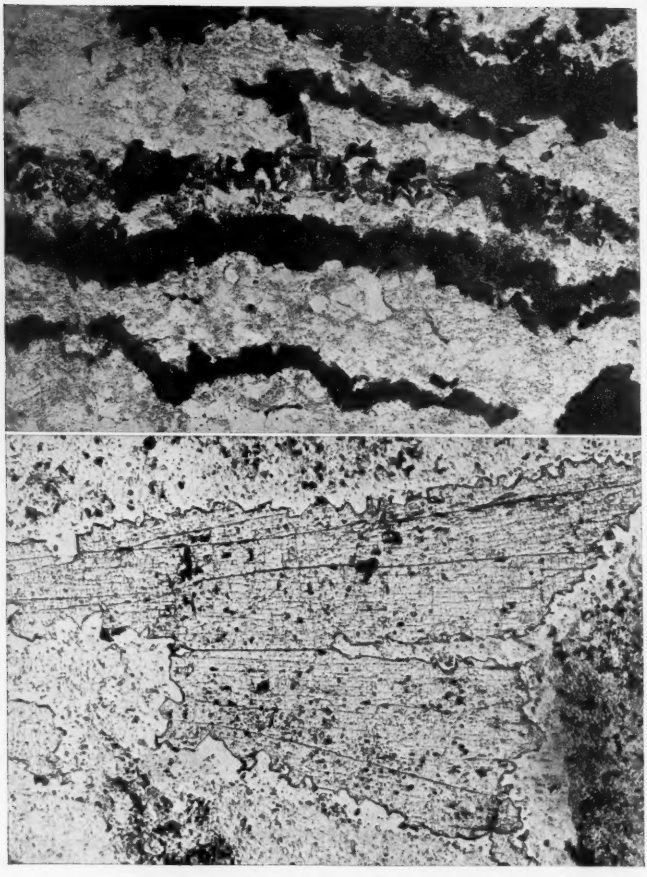

FIG. 7 (top). Originally zoned carbonate replaced by quartz; in second dark band from bottom are carbonates of two different indices; quartz has replaced the lower index carbonate more readily. × 24.

FIG. 8 (bottom). Quartz which has replaced barite is clearer than the surrounding quartz and sericite, which has replaced wall rock directly. Note euhedral crystal boundaries of the replacing quartz. Banner Vein. × 100.

time of deposition. For instance, pyrite and sphalerite are early minerals, and galena and chalcopyrite are late. But pyrite is closely associated positionally with chalcopyrite, and sphalerite with galena.

VEINS SOUTH OF STONY MOUNTAIN.

Specimens were collected and examined by the author from the Virginius, Terrible, and some minor veins south of Stony Mountain. The gangue minerals in these veins are: quartz, barite, sericite, beidellite, calcite, rhodocrosite, and other carbonates. Metallic minerals present are: galena, sphalerite, pyrite, tetrahedrite, arsenopyrite, marcasite, and minor covellite. All the tetrahedrite and some of the galena are argentiferous.

The initial stages of mineralization are best recorded in the minor veins, where later mineralization has not been intense. Barite is the first vein mineral recorded, developing in plates in the wall rock and the vein; probably alteration of the wall rock to fine-grained quartz, sericite, and pyrite accompanied and preceded this. Carbonate was then deposited in open spaces and as replacement of barite; this carbonate shows a zonal structure, some being manganiferous (Fig. 7). These early gangue minerals were attacked later by sulphides and quartz (Figs. 7 and 8).

In the Terrible and Virginius veins, corrosion by later mineralization was so intense that the early carbonate and barite were almost completely destroyed. Incidentally, this suggests a reason why veins high in barite are not usually productive; the quartz-sulphide mineralization has not been intense enough to clear out the barite. As deposition proceeded along fissures, flow became concentrated along certain shoots on the fissures. Here the quartz-sulphide mineralization was heaviest and destroyed barite and carbonate, so that the only evidence of their former presence is in residual textures in the quartz and sulphides (Fig. 9). Outward along the fissure away from the main shoots of flow, the amount of quartz and later sulphides diminishes and the veins are composed dominantly of the early barren gangue.

Probably the first stage of mineralization in the Virginius and Terrible veins consisted in attack on the wall rock, principally by the development of fine-grained quartz and sericite; as mineraliza-

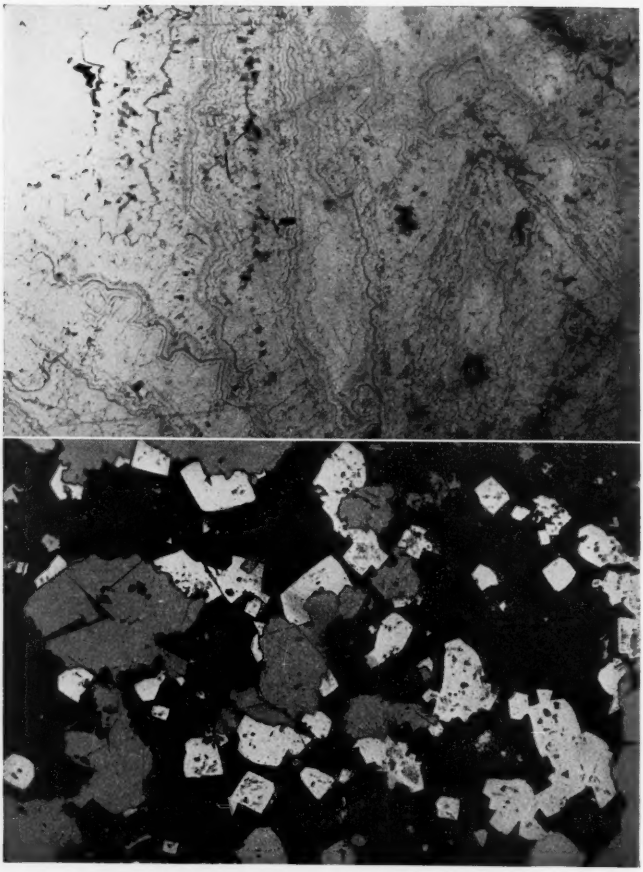

FIG. 9 (top). Platy structure in quartz inherited from barite. Quartz has encrusted and completely replaced barite. Virginius Vein (surface). × 9.

FIG. 10 (bottom). Galena (gray) corroding early pyrite crystals (white), which in turn replace carbonate (black). Galena has also corroded carbonate. Terrible Vein, 3 Level. × 55.

tion continued, this wall-rock alteration worked out farther from the vein. The hydrous aluminum silicate, beidellite, probably developed early from gouge in the fissure. Vein minerals were introduced in the following order: barite (now completely removed), carbonate, early sulphides, most of the quartz, late sulphides, and late quartz. Both the early and the late sulphides seem closely associated with the main quartz mineralization, which they precede and follow. The early sulphides include sphalerite, pyrite, arsenopyrite, and marcasite. These sulphides molded about the barite, preserve its platy structure, although this mineral has now been completely replaced by quartz. Sphalerite is in large masses, molding around the barite plates. Arsenopyrite grows out from the barite plates; marcasite together with some sphalerite replaces the plates themselves. Some pyrite is also perched on the plates, but most of this is in scattered grains and crystals. Arsenopyrite characteristically occurs at the border of sphalerite and gangue. Pyrite is definitely later than arsenopyrite, and is corroded by sphalerite.

The main quartz mineralization followed the early sulphides, replacing barite and carbonate. Some quartz formed in open spaces, growing out from the early minerals in euhedral crystals showing many stages of growth. The outlines of earlier quartz crystals are preserved by bands of inclusions of liquid or gas and of solid particles. The present structure of the quartz, as seen with crossed nicols, cuts across these pre-existing crystals; there must have been some recrystallization of quartz into larger units. A minor amount of carbonate is associated with and later than the quartz.

Toward the end of the main quartz mineralization, tetrahedrite, chalcopyrite, and galena were deposited, filling in open spaces between quartz crystals and corroding the early sulphides (Fig. 10). Thus, the deposition of the silver-bearing minerals was concentrated in and near the open spaces existing after deposition of the bulk of the quartz (Fig. 11). Chalcopyrite is minor in amount and its position in the sequence relative to the other two late sulphides could not be exactly determined. Galena followed

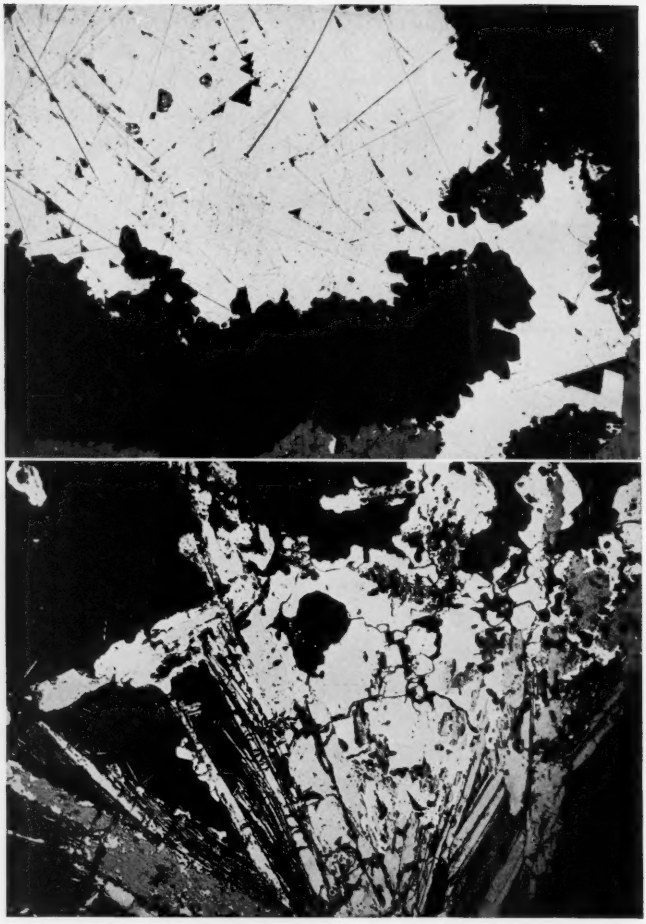

FIG. 11 (top). Vuggy quartz (black) filled in by late galena (white); quartz has grown on early sphalerite (dark gray), seen at bottom edge of picture. Virginius Vein, Revenue Tunnel. × 50.

FIG. 12 (bottom). Specularite plates (light gray) replaced by pyrite (white) and quartz (black). Magnetite (darker gray) has replaced the specularite plates internally at the lower left. Camp Bird Vein. × 30.

tetrahedrite. The three late sulphides fill in between the quartz, so that the euhedral outlines of quartz crystals are very apparent against them; the boundaries of such earlier sulphides as sphalerite are irregular against quartz (Fig. 11). In some instances, of course, galena and tetrahedrite, by replacing sphalerite, have inherited its irregular boundary against quartz.

The last event in mineralization was the deposition of a crust of quartz crystals. It must be noted that although the bulk of the quartz was deposited between the early and the late sulphides, some quartz was deposited more or less continuously throughout mineralization.

CAMP BIRD VEIN.

The Camp Bird vein is compound, according to Spurr, consisting of a silver-base metal vein cut by a gold-quartz vein.[30] The author is unable to offer any comment on the field relations of the vein, but will confine remarks to a description of specimens collected by Professor Graton. The study of these specimens suggests that the two separate mineralizations may be interpreted as phases of the same process. Relations between minerals are so complex here that the scattered observed facts of relations between individual minerals will be described first.

Relations of Gangue Minerals.—Gangue minerals include quartz, carbonate, adularia, epidote, zoisite, chlorite, fluorite, kaolin, sericite, and barite. Epidote and chlorite are found in the deeper and easternmost parts of the vein, associated with specularite.

Adularia was one of the earliest minerals to form, occurring in large masses and in small rhomb-shaped crystals. It is corroded by quartz, kaolin, carbonate, and zoisite. Probably some quartz formed early, before the completion of deposition of adularia; but most of the quartz in contact with adularia corrodes it. Quartz which has replaced adularia is frequently seen to be filled with fine, platy or needle-like inclusions, probably residual from the adularia.

Quartz attacks adularia from the margins, but within the large adularia crystals is abundant alteration to kaolin, carbonate, and

[30] Spurr, J. E.: *Op. cit.*, p. 138.

zoisite. The amount and pattern of alteration within the adularia is the same, regardless of the minerals involved. Thus it seems likely that one of the secondary minerals developed first and the later ones attacked the first rather than adularia. The alteration of adularia to kaolin involves but a slight change in composition and presumably occurred first.

Fluorite grains in carbonate are rounded and corroded; a few tiny barite residuals were also observed in carbonate.

Epidote occurs in small pleochroic green prisms; some aggregates of epidote have shapes suggesting replacement of an earlier mineral, perhaps adularia; epidote is slightly corroded by quartz and is earlier than some of the carbonate. Chlorite is later than calcite and epidote, occurring near the latter, and in streaks along calcite cleavages.

The place of carbonate in the sequence is somewhat uncertain. There was more than one period of deposition of carbonate, the higher index (manganiferous) carbonate being earlier. Most carbonate appears older than the quartz with which it is in contact; some antecedent veinlets of carbonate are seen in quartz, but some carbonate is associated with and later than quartz.

Relations of Metallic Minerals.—Metallic minerals include pyrite, sphalerite, galena, chalcopyrite, hessite, gold, specularite, and magnetite.

Specularite is in sheafs of radiating plates, corroded by pyrite and replaced internally by magnetite (Fig. 12). Quartz corrodes pyrite and specularite.

Sphalerite, like the iron minerals, preceded the main quartz mineralization and is corroded and cut by quartz. The fracturing of sphalerite and recementing by quartz is very apparent megascopically. Sphalerite and the iron minerals are rarely in contact, but in one section pyrite was seen to precede sphalerite.

Galena and chalcopyrite were late sulphides, filling in vugs between quartz crystals and corroding the earlier sulphides. The preferential replacement of sphalerite by galena has resulted in such a close association of these two minerals that a megascopic examination might suggest that galena preceded quartz. Perhaps

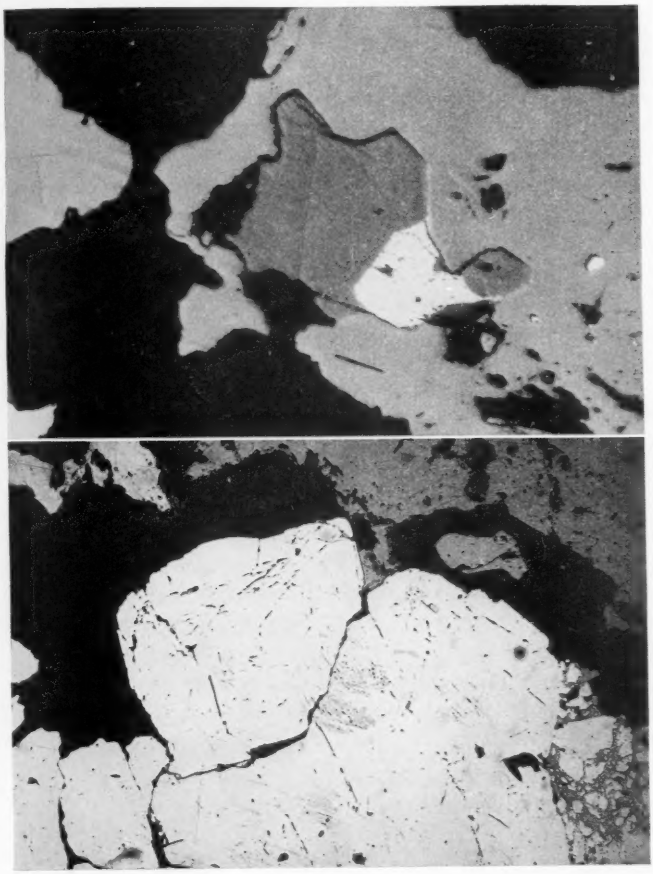

FIG. 13 (top). Gold (white) in chalcopyrite (dark gray) and in pyrite (light gray). Camp Bird Vein. × 800.

FIG. 14 (bottom). Typical sequence; the early pyrite (white) is veined by quartz (black); also quartz crystals are perched on pyrite. Late chalcopyrite (gray) has corroded both pyrite and quartz. Handicap Vein, Treasury Tunnel. × 32.

this may be a reason why Spurr spoke of a base-metal mineralization preceding the gold-quartz vein. Chalcopyrite selected pyrite as the particular victim of its attack. Galena followed chalcopyrite in time of deposition.

Hessite [31] was seen in one specimen and gold in several. The hessite occurs in galena and contains specks of gold. Gold was seen in galena, chalcopyrite (Fig. 13), hessite, pyrite, and specularite. The association of specularite with gold indicates that specularite is an integral part of the gold-quartz vein. Probably the introduction of gold occurred about the time of the chalcopyrite-galena mineralization.

Summary.—Although additional facts supplied by field study may modify the sequence here suggested, the obvious complexities of mineral relationships in the Camp Bird vein are interpreted as follows:

Early in the process of vein formation, adularia, some high-index carbonate, and some quartz formed. Then succeeded a period in which fluorite and kaolin were deposited, the former in carbonate, the latter replacing adularia. The work of Day and Allen [32] on the hot springs near Mount Lassen suggests that deposition of kaolin necessitates a somewhat acid solution. The early high-index carbonate was corroded by this acid solution. The acid condition did not persist, for carbonate was again deposited, corroding kaolin and fluorite and forming around cor-

[31] No telluride has been previously identified from the San Juan region, although chemical analyses revealed the presence of tellurium at Camp Bird. In view of this, the description of hessite is appended.

Locality—King stope, 160 feet above third level.

Relations—seen only in galena.

Color—slightly darker and browner than galena.

Anisotropic—seen to be irregularly twinned.

Hardness—B — or A + (Talmage scale).

Chemical tests:

negative to KOH, KCN, HCl.

HNO_3—blackens quickly.

$FeCl_3$—quickly stains irridescent.

$HgCl_3$—stains quickly.

Composition—Ag_2Te. Silver and tellurium found in spectrographic analysis by Mr. G. A. Harcourt. Same elements proved by microchemical tests.

[32] Day, A. L., and Allen, E. T.: Carnegie Inst. Pub. 360, p. 140 *et seq.*, 1925.

roded residuals of early carbonate. Epidote, deposited in the deeper levels, preceded this carbonate somewhat, and chlorite followed carbonate.

The early metallic minerals were introduced about the time of epidote-carbonate formation, including hematite, magnetite, pyrite, and sphalerite.

The bulk of the quartz was introduced after the formation of the minerals above mentioned. Toward the end of the main quartz mineralization, chalcopyrite, galena, hessite and gold were deposited. The later sulphides replace earlier sulphides, but fill in between quartz crystals with only slight replacement.

Association of minerals is determined not only by closeness in time of deposition but by some innate chemical affinity. The iron oxides and pyrite are rarely in contact with sphalerite, although all were formed before the main quartz mineralization. Galena, which formed after the main quartz mineralization, is intimately associated with sphalerite.

The last phase of mineralization was minor deposition of calcite and a crust of vuggy quartz.

VEINS NEAR THE TREASURY TUNNEL.

The author collected specimens from the Handicap and two other veins cut by the Treasury Tunnel, and examined them microscopically. The near-by Barstow vein was examined megascopically.

The veins formed in part by replacement of the wall rock. Wall-rock textures are preserved in the quartz vein by clots of sericite. Some apatite from the wall rock is seen corroded in the quartz vein. The first stage in mineralization was the alteration of the wall rock to fine-grained quartz, sericite, and relatively large cubes of pyrite. Adularia and fluorite were early gangue minerals, preceding the bulk of the vein quartz.

The quartz in these veins is somewhat coarser and more equigranular than that in the veins to the northwest, fitting well with the idea that this region represents a somewhat more intense type of mineralization than that to the northwest. The relation of

quartz to pyrite is interesting. Quartz penetrates and grows on large pyrite masses (Fig. 14). Also, quartz forms haloes around pyrite cubes in wall rock. Similar quartz borders around pyrite have been called pressure fringes, the implication being that the pyrite grains have been partly rolled or rotated out of their sockets. Such an explanation can hardly hold for quartz fringing pyrite here; the quartz builds out in entirely random fashion from the pyrite cubes, occurring on any one or all sides of the pyrite, and replaces the wall rock.

Chlorite was seen zonally included in quartz crystals, marking out a former limit of growth of the quartz. Apparently it formed toward the end of the quartz mineralization, denoting a slight cessation in deposition of quartz at that time.

Besides pyrite, specularite and sphalerite precede the main deposition of quartz. Specularite is very minor in amount, being represented by a few minute blades enclosed in pyrite. Chalcopyrite and galena were deposited toward the closing stages of quartz mineralization (Fig. 14).

YANKEE GIRL CHIMNEY ORE.[33]

As in the lode ores, barite is an early mineral; sericite and chlorite can be seen interstitial to the barite plates (Fig. 15). The structure of both sericite and chlorite is that of chlorite, suggesting that sericite has replaced chlorite.

The relation between pyrite, enargite, and quartz is complex. Apparently an oscillation in conditions determined which of these minerals should form. In places, crystals of pyrite and quartz are corroded by enargite; this corrosion may bring out zonal structure in the pyrite (Fig. 16). In other instances, pyrite and quartz have grown on top of elongated prisms of enargite.

The relation between enargite and tennantite in the Yankee Girl chimney ore differs greatly from that observed in ore from Butte and the Peruvian camps, in which tennantite is distinctly later than enargite, veining and corroding it. In the Yankee Girl

[33] Workings in the chimney ore deposits are not now accessible, but specimens collected by Professor Graton from the dump of the Yankee Girl chimney were studied microscopically. As would be expected, none of the phenomenally rich secondary ore was found on the dump.

FIG. 15 (top). Pyrite crystals (white) replacing barite plates and interstitial gangue; sphalerite (dark gray), galena (light gray), and tennantite (medium gray) do not replace barite but have replaced the interstitial gangue of sericite and chlorite. Yankee Girl Chimney. ×32.

FIG. 16 (bottom). Zonal structure in a pyrite crystal (white) brought out by selective attack of enargite on certain zones. To the right, the enargite has been etched with KCN to bring out the blebs of tennantite and galena in it. Yankee Girl Chimney. ×115.

chimney, the enargite and tennantite are intimately intergrown (Fig. 16). The geometric relation is not very conclusive, but the suggestion is that the two were essentially contemporaneous but that deposition of tennantite continued after that of enargite.

The sulphides whose relations have not been discussed are: sphalerite, chalcopyrite, and galena. Galena is closely associated with and somewhat later than tennantite. Chalcopyrite and galena occur in small blebs in the tennantite. Sphalerite was present in only a few specimens, antedating the galena.

SUMMARY OF PARAGENESIS AND CONCLUSIONS.

The veins of the western San Juan region exhibit the following general sequence:

1. Beginning of alteration of wall rock to quartz and sericite. As mineralization continued, alteration gradually worked out farther from the fissure.

2. Development of early gangue minerals: barite, manganiferous carbonate, adularia, fluorite, kaolin, epidote, carbonate, chlorite, and some quartz.

2. a. Formation of the early metallic minerals: specularite, magnetite, pyrite, arsenopyrite, marcasite, and sphalerite. Some of these early metallic minerals preceded carbonate and chlorite, but in general they formed after the early gangue mineralization and closely preceded the main quartz mineralization.

3. Bulk of the quartz (some quartz before and some continuing after this), closely followed by—

4. Later sulphides: tetrahedrite, chalcopyrite and galena. Gold and hessite were also introduced at this time.

5. Barren gangue—calcite and semi-transparent quartz.

The fact that the same general course of events was followed in several fissures does not imply that deposition of any one mineral occurred in different fissures at the same time.

From the microscopic study, certain conclusions can be drawn:

1. The importance of the process of replacement in the formation of the veins is definitely shown by microscopic examination. Pseudomorphs, residual textures, and corrosion of minerals all point to much replacement.

2. The concept of an ore magma must be abandoned for the San Juan veins. Replacement necessitates considerable removal of material. The material could hardly be removed except by a tenuous medium.

3. The material in the middle of a vein is not necessarily the last deposited. It may, for example, be a replaced septum of wall rock.

4. Deposition of tetrahedrite, chalcopyrite, galena and gold closely followed deposition of most of the quartz. Where the flow of mineralizing solutions, in consequence of clogging of channelways by deposition, had been so diminished at the time of quartz mineralization that the early gangue minerals were little attacked, the ensuing silver or gold mineralization would also be poorly developed. Thus, portions of a vein high in barite are not likely to be productive.

5. Precipitation of the later metallic minerals is favored by the presence of early metallic minerals. Galena and tetrahedrite formed near sphalerite; gold near galena, chalcopyrite, and specularite.

6. Deposition of minerals in the San Juan region shows some "reversals" in sequence, probably due to overlap and contemporaneous deposition of minerals.

GENETIC CLASSIFICATION OF THE ORE.

Lindgren, who is largely responsible for the classification now most widely accepted, considers the San Juan deposits to be epithermal.[34]

The San Juan deposits exhibit certain notable deviations from the typical epithermal deposits of Lindgren. These deviations are in the direction of the characteristics exhibited by deeper-seated deposits. The distinctive features are listed:

1. The San Juan veins are remarkably regular. Some of the most continuous stopes in the world are found here. The Smuggler vein has been mined continuously for over 8,000 feet horizontally and 2,300 feet vertically.

2. The veins are richer in sulphides than typical epithermal veins; this is especially the case for the veins in the Silverton quadrangle.

3. In alteration of the country rock, chlorite is low. The regional alteration is to carbonate, chlorite, and sericite, with carbonate far in excess of chlorite. Adjacent to veins, the wall rock is altered to fine-grained quartz and sericite.

4. The ores include some minerals not usually found in epithermal deposits, such as specularite, magnetite, arsenopyrite. Enargite, which occurs here, is also more at home in deeper-seated deposits than in the epithermal type.

The northwestern area of precious metal veins with minor sulphides might perhaps be considered as representative of the deeper

[34] Lindgren, W.: Mineral Deposits, p. 503, 1933.

portions of Lindgren's epithermal zone. But if the base-metal veins of the Silverton quadrangle were judged solely on their own merits and classed without reference to the veins farther west, they would doubtless be called upper mesothermal. Between the types of veins in the two districts is a complete gradation.

Graton has recently proposed the leptothermal class to comprehend ore deposits which bridge the gap between typical epithermal and mesothermal ores.[35] The leptothermal class is to be favored for the San Juan deposits not only because of its convenience in designating just the features that are their characteristics, but also because of the emphasis Graton's division places upon gradation between mesothermal and epithermal zones. Lindgren apparently decries the likelihood of such a gradation, stating: "The epithermal veins were formed from hot solutions which had their origin in the deep reservoirs where the magma was differentiated into the various types of flow rocks, and not, like most mesothermal and hypothermal deposits, in batholithic intrusions nearer to the surface."[36] Relations in the San Juan region cast doubt on that hypothesis. Not only is there gradation between deposits partaking of epithermal and of mesothermal characteristics, but there can be little doubt that intrusion and mineralization were closely connected processes. The down-faulted block in the Silverton quadrangle was a focal area for both intrusive activity and mineralization. The lateral variation in the ores away from the down-faulted block is of the same sort as is found in mesothermal deposits and is difficult to understand on the basis of a deep-seated source, which would hardly introduce a horizontal temperature variation of this type far above it. The presence of specularite in some veins near the down-faulted block as well as at depth in the Camp Bird mine also points to a not far distant source. The explanation most consistent with the facts is that both the intrusive stocks and the mineralizing solutions were derived from magma reservoirs not far below the present surface.

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Feb. 3, 1936.

[35] Graton, L. C.: ECON. GEOL., vol. 28, p. 537, 1933.
[36] Lindgren, W.: *Op. cit.*, p. 455.

MECHANICS OF METASOMATISM.

GEO. W. BAIN.

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INTRODUCTION.

THE importance of capillary openings in metasomatic replacement was discovered as a by-product of quantitative study of solution effects on building stone. Experimental work was recently undertaken by the author to determine cause for the limited use of certain marbles and to find a treatment which might extend the use of these stones. This required information as to why certain white marble dried up rapidly, while alternating green silicate bands remained damp for a long period, and also on the nature of ageing of building stone. The first investigation

showed relation of pore width to location of mineralization in such form as to indicate the mechanics of silication of limestone and the cause of banded structure in metasomatic deposits made in a rock that had been chemically homogeneous (Fig. 1). The

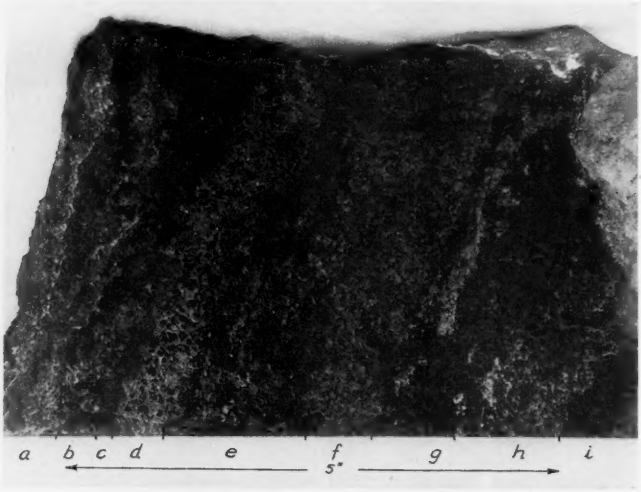

FIG. 1. Photograph of polished slab of Bernardston magnetite ore showing banding found in many metasomatic deposits. Bands *a*, *c*, *e*, *g*, *h*, and *i* contain magnetite principally; bands *b*, *d*, and *f* contain garnet and pyrite principally. Magnetite bands have magnetite and hematite (gray), occasional amphibole (solid black), and carbonate (white). The garnet bands have amphibole (solid black), garnet (fractured black), vesuvianite (gray) and pyrite (very light gray).

second part indicated at least one factor limiting metasomatic deposits to rocks of low porosity and causing a high degree of replacement in the massive parts of epithermal veins (Fig. 2).

General Setting for Investigation.

The case of West Rutland crystalline limestone is selected specifically because more information is available for it, principal

mineralization stages are well represented, and the cross-section of the affected zone is well exposed. This crystalline limestone is used largely for interior marble, and more than twenty acres of the deposit are exposed on the walls and pillars of a single quarry.

Geology of West Rutland Deposit.—The West Rutland valley in Vermont is underlain by Chazy, Black River, and Trenton limestone. The beds dip eastward on the west flank of a syncline. Dolomite interbedded with the limestone broke along numerous fractures but did not recrystallize appreciably during folding. Original dark gray to black limestone changed to graphitic, gray, crystalline limestone, and calcite recrystallized in this process. Flowage fold structures are superimposed on the main fold, and the forces producing them have oriented the vertical axes of calcite crystals almost perpendicular to the axial planes of the minor folds (Fig. 3).

Graphite has been removed from crystalline limestone along the dolomite beds, and the adjacent stone is white; but within the flowage zone most crystalline limestone is white, and dolomite is altered to green silicate bands containing sericite, chlorite and actinolite, especially where all graphite is removed from the crystalline limestone. Solutions are believed to be responsible for silication of the dolomite and removal of the graphite.[1] Late pyritic mineralization occurs in one band of white marble but disappears where this same bed remains graphitic.

Solution Channels and their Measurement.—Solutions appear to have played the leading rôle in the mineral changes and vied with mechanical movements in causing many textural and structural modifications in the crystalline limestones of Vermont.[2] Openings are essential to passage of these solutions, so porosity tests were made for the amount of water the rocks *could* take up; others for absorption to determine amount of water the rocks *would* take up; and still others for relative permeability to determine the relative *rate* at which the rocks took up water. In Table I, these rocks as might be expected, occupy approximately the

[1] Bain, G. W.: Calcite Marble, ECON. GEOL., vol. 29, pp. 133–138, 1934.
[2] *Op. cit.*, p. 139.

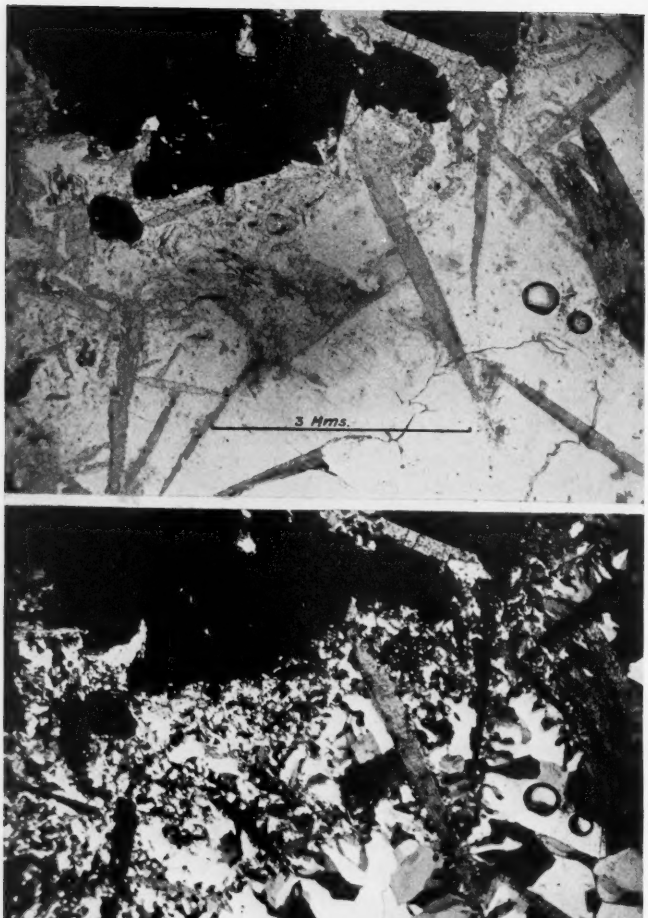

FIG. 2.

same relative order, whether the basis be porosity, absorption or relative permeability.

Tops of large blocks standing on moist ground become damp in the white absorptive sections before any water effect is noticeable in the green-veined part, corroborating the tests made in the laboratory on a small scale. Experiment showed that absorption tests made with proper care were as satisfactory for crystalline limestone from a given deposit as porosity or permeability determinations, and they are the principal type used in this study.

VARIATION OF CHANNEL SPACE AND MINERALIZATION.

Absorption tests show that, bed for bed, the mineralized sections of the crystalline limestone have lower absorption and lower porosity than the white marble; nowhere is the white marble less absorptive or less porous than the adjoining silicated bands, and differences of 15 per cent. are not uncommon. Sulphide mineralization is low; pyrite occurs sparingly in some silicate bands but is found principally in the intervening white marble, especially at the bottom of the deposit. Parts of this bed lacking sulphides have absorption up to 0.2681 per cent. and average 0.2441 per cent.; absorption by the sulphide-bearing part of the same bed is only 0.1475 per cent. The cause of greatest mineralization in rocks having least channel space and almost complete spatial sepa-

FIG. 2. Photomicrographs showing replacement of massive barite by quartz and encrustation of barite plates occurring in open spaces by the same mineral. Above: ordinary light. Below: same with crossed nicols. Upper part of area (black) is sphalerite encrusting barite plates (elongated crystals) in a massive part of vein. Lower part shows barite plates in coarse quartz; the plates have straight, smooth edges. The space between the lower and upper parts contains barite plates with concave marginal indentations due to replacement by quartz (white). Restoration of the linear outlines shows this central part of the figure to have been solid barite before replacement. The lower figure shows the fine grain of the replacement quartz in contrast to the coarse encrusting quartz. Both figures together show the extent of replacement in narrow openings between closely packed crystals and lack of replacement of crystals in large cavities.

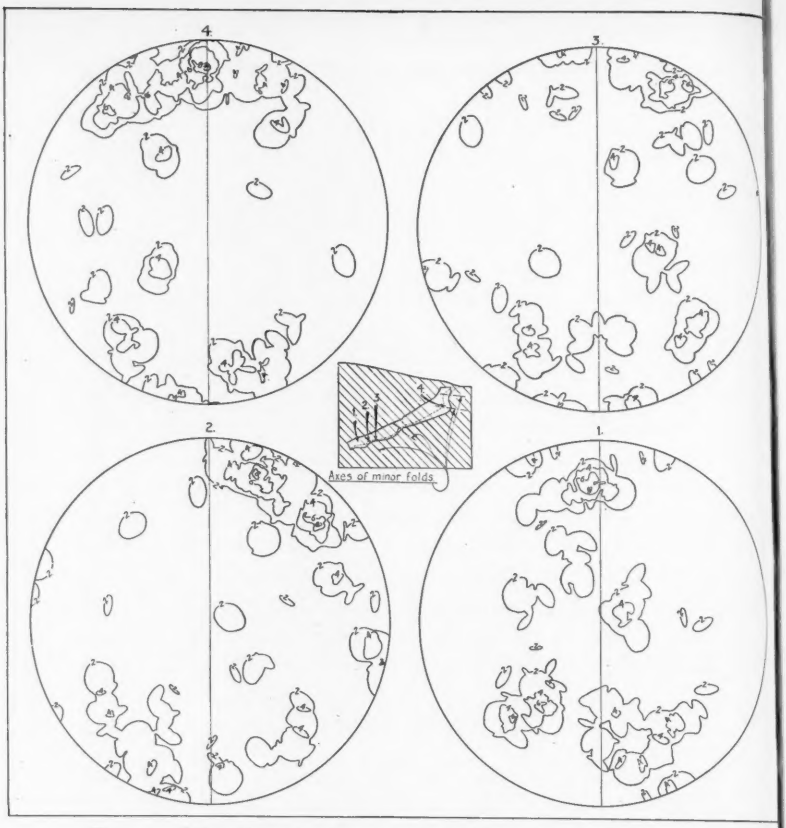

FIG. 3. Orientation diagrams showing internal crystal adjustments accompanying deformation of crystalline limestone during mineralization. These diagrams are plotted on a spherical projection and represent the extent of orientation of the vertical axes of *untwinned* calcite crystals. The numbered contours represent the number of vertical axes intersecting one per cent. of the area of the sphere within the contour. Each orientation diagram occupies a position parallel to the position indicated on the central location figure. Greatest alignment of vertical axes occurs at locations 2 and 4, which are on the fold axes. More than fifty other diagrams agree with these in showing higher degree of alignment along the fold axes than at any other place at West Rutland. Progress of studies on crystalline limestone shows that the anisotropic qualities of calcite cause highly aligned rock to be more susceptible to solution attack than otherwise similar unoriented material.

ration of silicate from sulphide mineralization seems to be demonstrated by the following studies on the West Rutland crystalline limestone, and this in turn helps to explain the banded structure of many contact-metasomatic deposits.

Measurement of Effective Channel Space.

Absorption tests were carried out to determine the channel space in silicated zones, in sulphide-bearing zones, in highly folded white marble, and in white marble of the corresponding bed which had been affected least by mineralizing solutions or deformative movements.

Absorption Tests on Silicated Zones.—Silicated zones in the West Rutland deposit are the dark bands of the Double Belt layer, the green stripe of the Hard layer, the Jackman, the Crinkly, and the Striped Brocadillo. Absorption tests on the green stripes of these marbles and of the unsilicated white marble associated closely with them are given in Table I. All stone permeated by silicating solutions is less porous and less absorptive and passes solutions more slowly than the bordering unsilicated marble. Tests made on other crystalline limestones show this to be as true in them as at West Rutland.

TABLE I.

PROPERTIES OF SILICATED AND UNSILICATED WHITE CRYSTALLINE LIMESTONE.

Rock No.	Porosity		Absorption		Permeability *	
	Silicated	White	Silicated	White	Silicated	White
1	0.1632	—	0.1543	0.1700	38	—
2	0.1737	0.2395	0.1466	0.2395	31	21
3	0.2350	0.2849	0.1920	0.2137	44	38
4	0.2654	0.2861	0.2167	0.2367	39	38
5	0.1850	0.2514	0.1770	0.2060	45	33

* Porosity and absorption are given in percentage of water by weight taken up by the rock.

Permeability is given in terms of number of minutes for water to saturate a piece of rock 1.5 inches thick under atmospheric pressure.

1. Double Belt layer.
2. Hard layer.
3. Jackman layer.
4. Crinkly layer.
5. Brocadillo layer.

Absorption tests on sulphide-bearing white crystalline limestone.—One bed of white crystalline limestone locally has dark veining due to minute pyrite disseminated along certain zones, and is almost free of it in others. Absorption is much lower for highly veined white stone than for unveined or only slightly veined parts of the same bed, as shown in Table II.

TABLE II.

RELATION BETWEEN SULPHIDE MINERALIZATION AND SPACE FOR SOLUTIONS.

Type of Crystalline Limestone	Average Absorption	Absorption Range
White crystalline ls., unveined	0.2441	0.2355 to 0.2681
White crystalline ls., fine, slightly veined	0.1996	0.1941 " 0.2052
White crystalline ls., coarse, slightly veined	0.1705	0.1655 " 0.1750
White crystalline ls., highly veined	0.1475	0.1389 " 0.1598

Crystalline limestone containing metasomatic pyrite or limestone that has been recrystallized by solutions is less absorptive than stone not showing these changes. The pyritic white stone does not lie immediately adjacent to the bounding, silicated bands of low absorption of the Double Belt and Rutland Italian layers, but is separated from them by more highly absorbing white stone (Fig. 4).

The crystalline limestone has remained blue, due to disseminated graphite beyond the zones affected by the silicate- and sulphide-bearing solutions. This and other evidence cited[3] indicates that all sections of white marble have been affected somewhat by solutions.

Similarity of absorption tests on Yule marble.—The Yule marble of Colorado is quarried from the Yule limestone. It has considerable golden-colored veining of quartz, muscovite, and hastingsite, sometimes at a pronounced angle to the bedding planes; less generally there are bright green veins of quartz, chlorite and a green amphibole approximating kuperferite. Absorption of highly veined stock averages 0.115 per cent.; absorption of the immediately adjacent white or statuary stock averages 0.136 per cent.

One prospect tunnel has much sphalerite and pyrite deposited

[3] *Op. cit.*, pp. 136–138.

later than the silicates and associated with dolomitization. The principal sulphide mineralization is not in the silicated zone, but, as at West Rutland, is in the intervening white marble.

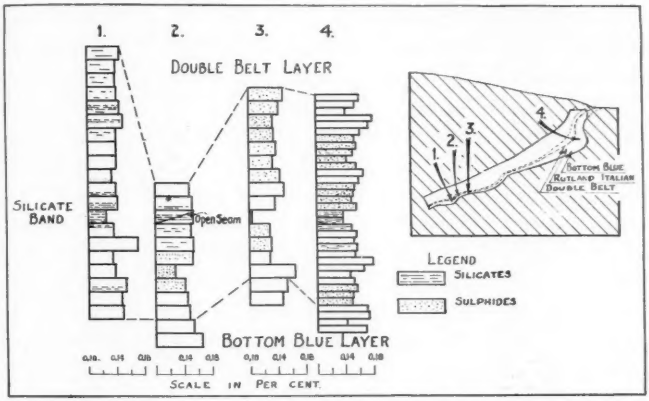

FIG. 4. Diagram showing variation of pore space in bed of crystalline limestone in relation to zones of deformation and zones of mineralization. (See also Fig. 3.) Each column in the diagram represents a two inch sample cube across the Rutland Italian bed at West Rutland. The location diagram at the right shows that the more absorptive (more porous) crystalline limestone series at locations 2 and 4 are on fold axes; their values average much higher than where the beds are less disturbed, at cross sections 1 and 3. Variation in relative intensity of mineralization is indicated by intensity of lining or stippling. Note that the low absorption places are those of abundant silicates or sulphides and that the unmineralized and almost unchanged Bottom Blue crystalline limestone has the highest absorption.

Explanation of Absorption Variation in Marble.

The green bands of the Double Belt and Hard layer marbles were much fractured dolomite beds before silication.[4] The Jackman layer may have been dolomite, but the Crinkly and Brocadillo were originally the ordinary type of permeable blue crystalline limestone. All dolomite beds are much fractured, and blue crystalline limestone immediately adjacent is bleached white even

[4] *Op. cit.*, p. 136.

where the deposit shows no other evidence of the action of solutions. The fractures in dolomite appear to have afforded good openings for solutions and to have been the original entrance channels for the silicating solutions. But the silicated zones, marking the early channelways, have now lower channel space than the bordering crystalline limestone (Table I and Fig. 4). The best explanation of lower channel space in the mineralized beds, and also in the mineralized parts of a bed, than in unmineralized sections seems to be that deposits from solution occupy some of the space of the more porous rocks. The mechanism for this change would appear to be extremely complex, because these established paths remained channels for solutions until the channel space had been reduced below that of the bordering crystalline limestone. Any explanation of this behavior of solutions passing through the chemically homogeneous calcite rock, which went to make the Crinkly and Brocadillo layers, lies in physical changes affecting the solutions.

The major physical control of the solutions is outlined by Van't Hoff's law, which states, "A solution in equilibrium undergoes that change at lowered temperature which is accompanied by liberation of heat." This law underlies most modern conceptions of mineral deposition; its operation in causing mineral precipitation from solutions passing into zones of dropping temperature has been summarized ably by Lindgren,[5] Graton,[6] and others. Within the limited confines of mineral deposits and contact-metasomatic zones the general equilibrium conditions maintained by operation of the Van't Hoff law are disturbed by other factors which operate to control the locus of liberation of heat and mineral precipitation from migrating solutions and to reduce effective channel space.

Saturated solutions moving in the restricted space of the channelways are affected by pressure changes and pressure is affected in turn by velocity changes in the moving solutions. According

[5] Lindgren, W.: Mineral Deposits, p. 25, 140, 236. 3d Ed., McGraw-Hill Book Co., New York, 1928.

[6] Graton, L. C.: Depth Zones in Ore Deposition. ECON. GEOL., vol. 28, pp. 521, 1933.

to Le Chatelier's law, "A solution in equilibrium undergoes that change, following pressure decrease, which is accompanied by an increase in volume, and that change occurs, when pressure increases, which is accompanied by a decrease in volume." The volume of most solutions is less than the sum of the solute and solvent, so that decrease in pressure may be expected to cause precipitation of the solute. One cause of pressure change to bring about precipitation in channelways of varying cross-section is given by the velocity-pressure relationship indicated by the Bernouilli principle, that "pressure on the moving solution varies inversely as the square of the velocity." Velocity must increase in constricted sections and diminish in wide openings. The permeable zones are decidedly lenticular and bifurcating, so that part of a solution moving along them is diverted into side channels and, enters zones of narrower openings at the end of a lens before passing into another permeable zone, and velocity increases in the constricted section over that in the more open part on either end. Velocity increase in constricted sections will cause pressure decrease, according to the Bernouilli principle, and according to Le Chatelier's law this will induce a tendency to volume increase and precipitation of minerals in narrow openings along the more porous initial channelways.[7] These precipitates will form confining walls for the solutions and maintain the solution courses even after mineralization has reduced the channel space in the main course below that in crystalline limestone beyond the walls formed by the Bernouilli effect. The effect of these confining walls upon the solutions in equilibrium may be likened to the confining effects of natural levees upon the waters of rivers in equilibrium.

Explanation of Separate Occurrence of Silicates and Sulphides.

Sulphides appear rarely in the silicated zones in the West Rutland and Yule crystalline limestone, indicating that the latest sulphide-bearing solutions avoided the silicated zones for the most

[7] Change in the solution is affected by concentration and surface energy of the solution, and under one set of conditions, described later, precipitation does not take place.

part, but entered the intervening more porous crystalline limestone and further reduced channel space. Explanation of mineral deposition to reduce porosity below that of surrounding stone and the occurrence of late stage minerals in separate bands required an adequate explanation of the abrupt shifting of solution paths.

Offsets of graphitic veins in blue crystalline limestone at West Rutland, and of silicate bands in the white variety at West Rutland, Pittsford Valley, Danby and Colorado Yule marble quarries, indicate that fracturing occurred even after the first stages of mineralization. Fractures in garnet, diopside, actinolite, and even in later metallic minerals of contact metasomatic deposits, indicate that fractures continued to open at intervals throughout the mineralization process. Any of these fractures would serve as rifts in the walls built along the solution channels by the combined Bernouilli and Le Chatelier effects, and would afford an outlet for the solutions from any channel which had become less permeable than the adjacent rock due to mineral deposition. Fractures crossing a more permeable zone would afford an outlet into it; this new zone becomes the locus for the later mineralization.

As long as intermittent fracturing recurs and mineralizing solutions continue to flow, shifts in channels may be anticipated, and each break will divert flow abruptly to the more favorable channel. Each new channel should have the effective channel space along it reduced by the combined Bernouilli–Le Chatelier effects just as along the first channel; this seems to have been demonstrated by Fig. 4 for the West Rutland crystalline limestones. This explanation is the only one occurring to the author which will account for the channel-space distribution and for occurrence of two distinct types of mineralization closely adjacent to one another yet completely separated at West Rutland. Vermont, and at Yule, Colorado.

Application to Mineral Deposition Studies.

Many metasomatic mineral deposits possess banded structure which cannot be attributed to composition differences in the replaced rock. The early silicates such as vesuvianite, wollastonite, diopside, garnet and other minerals of the skarn series occupy limited zones. The hard oxides such as magnetite and specularite follow and characteristically occupy zones distinct from the earlier silicated bands. The last group of minerals, including the sulphides and carbonates such as magnesite, siderite and ankerite, occur separate from the magnetite and specularite either in the silicated zones or in zones lacking minerals earlier in the paragenetic series. This mode of occurrence is illustrated remarkably well by certain features in metasomatic magnesite and dolomite deposits in the Grenville limestone, by the Bernardston magnetite deposit, and by the Sullivan lead and zinc deposit at Kimberly, B. C. The Bernardston, Mass. magnetite deposit is what might be described as a text-book case and will serve to illustrate all the points mentioned.

The Bernardston Magnetite Deposit.—This deposit is on the upper side of a recumbent syncline of lower Devonian limestone; the axial plane of the fold inclines about 15° eastward. Quartzite underlies the limestone and is underlain by graphitic phyllites of doubtful age. Magnetite and silicated zones occur at intervals along the hanging-wall contact of limestone with quartzite; limestone outside the metasomatic areas is relatively pure and carries numerous Helderbergian fossils. Fossils replaced by magnetite come from mineralized parts of the limestone.

Vesuvianite, tremolite (partly replaced by quartz), and garnet (partially altered to chlorite) constitute silicated zones one half to two inches wide. Magnetite replaces the garnet along fracture zones and occurs between the quartz replacements of the acicular tremolite, but makes up less than 10 per cent. of the silicated zones and comprises 95 per cent. of the intervening rock. Some bands are 70 per cent. siderite enclosing magnetite octahedrons. Magnetite is altered to hematite locally along cracks.

Minute veinlets of pyrite cut some of the magnetite, but late

pyritic mineralization is less than 1 per cent. of the magnetite bands. The sulphide minerals occur principally in the silicated zones or in replaced limestone bands lacking mineralization of the earlier stages. Pyrite is the chief sulphide; some chalcopyrite is present.

Blasting during operations, and weathering since the early part of the past century (when the deposit was last worked), have modified pore space so much that absorption tests on beds outside the metasomatic deposits are worthless. However, the abrupt shifting of solution paths from one zone to another during the early stage of magnetite mineralization, and from that path to another with the beginning of sulphide deposition, presents such close parallelism in behavior and distribution to the "levee" effect in the crystalline limestones of the marble quarries as to be accounted for most readily in the same way.

An alternative explanation exists if a definite break may be assumed between silicate-oxide mineralization and the sulphide-carbonate mineralization. This possibility is presented even though all the evidence favors a continuous overlapping series. Two solutions differing in surface tension and hence in absorption properties and having no common ions may conceivably be separated by a semi-permeable body with capillary openings large enough to permit the passage of one solution but not large enough for passage of the other. Some indication of this sort of filtration appears in wall-rock mineralization at Kirkland Lake, Ont., where the wider micro-fissures have both chlorite and carbonate mineralization and the narrower ones carbonate mineralization only.[8] On this basis, early silicate zones of metasomatic deposits are in the channelways; the solutions which deposited the magnetite filtered out into the less permeable zones from which silicate solutions were withheld. This explanation requires the late sulphide solutions to filter out from the silicate portion at West Rutland where magnetite is lacking, but remain with the silicates at Bernardston where the magnetite is present, which is incredible.

[8] Bain, G. W.: Wall-rock Mineralization Along Ontario Gold Deposits. ECON. GEOL., vol. 28, pp. 733–734, 1933.

Inconsistency in the mineral associates of the sulphides on this premise seems to indicate that the type of solutions does not determine what materials will be deposited in a given zone, but that the type of solutions passing when the walls of a channel are fractured controls mineral growth along the new path.

VARIATION IN CHANNEL WIDTH AND METASOMATISM.

A second singular feature of metasomatic deposits is partiality to formations or parts of formations possessing exceedingly low porosity. Quartzites are more subject to metasomatic replacement than sandstones, and crystalline limestones are replaced more often than very porous limestones; by contrast, cavities in cavernous beds and openings in breccias are usually filled, and replacement is negligible. Tests devised to reveal the ageing qualities of stones under solution attack revealed facts bearing upon the mechanics of metasomatism which seem responsible for this contrast. Chemical replacement is ion for ion and can take place in reactions between liquids or gases and solids; metasomatic replacement is a volume for volume replacement, and the reaction to yield the new material takes place in solution. Limitation of metasomatism to rocks of low porosity suggests that capillary, rather than larger pores, play an important part in causing solution of the solid phase of the system. Differences between the behavior of very porous rock and that of rock with very low porosity, in presence of saturated solutions, were studied in order to investigate the process of pore enlargement during metasomatism.

Enlargement of openings.

Eight calcite rock types were selected for study; one had extremely narrow capillaries and very low porosity; the second had narrow capillaries and low porosity; the third had narrow capillaries and high porosity; and the fourth and fifth had medium narrow openings and low porosity; the sixth and seventh had wide openings and medium porosity; and the eighth had extreme porosity and very wide openings. Each rock type was treated

with distilled water to measure the effect of un-ionized solutions on the walls of the openings. Absorption tests before and after repeated saturation and dehydration of the test pieces showed no effect. The test cubes were subsequently immersed alternately in saturated $BaCl_2$ solution and Na_2SO_4 solution in order (1) to

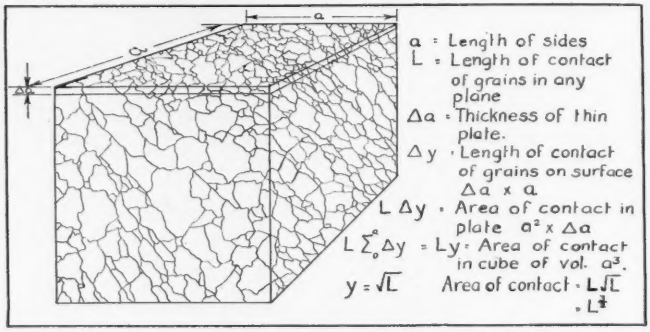
a
a = Length of sides
L = Length of contact of grains in any plane
Δa = Thickness of thin plate.
Δy = Length of contact of grains on surface Δa x a
L Δy = Area of contact in plate a² x Δa
L ∫₀ᵃ Δy = Ly = Area of contact in cube of vol. a³.
y = √L
Area of contact = L√L = L^3/2

FIG. 5. Diagram illustrating method of calculating the area of contact between grains comprising crystalline limestone.

cause precipitation of an insoluble salt in the openings, if precipitation could occur, and (2) at the same time to permit enlargement of the capillaries by solution of the walls. The rate of penetration of the test pieces by the $BaCl_2$ and Na_2SO_4 solutions is too rapid to allow excessive reaction between $CaCO_3$ and $BaCl_2$, before Na_2SO_4 and Ba Cl_2 come in contact. This treatment caused rocks with openings 32×10^{-7} centimeters wide to undergo greatest increase in absorption (representing widening of the openings) and least increase in weight (representing precipitation of $BaSO_4$ in excess of the $CaCO_3$ dissolved). (Table III.) Deposition of precipitated $BaSO_4$ filled 1.75 per cent. of the openings in the very porous limestone.

Location of Enlargement.—Increased absorption caused by salt solutions has been attributed to surface rupture by crystallization of salt in the outer capillaries. The outer quarter-inch of some test cubes treated in the above fashion was honed away to remove

TABLE III.

Relation between Amount of Replacement and Width of Openings.

TABLE III.

RELATION BETWEEN AMOUNT OF REPLACEMENT AND WIDTH OF OPENINGS.

Spec. No.	Amount of replacement of calcite									Width of openings			
	A	*B*	*C*	*D*	*E*	*F*	*G*	*H*	*I*	*J*	*K*	*L*	*M*	*N*
1	0.1598	.00436	0.1928	1	.0330	.000901	.0160	.000437	.000247	.001148	150.8	1851	.00000235	7.6
2	0.1068	.002915	0.2878	3	.1810	.004941	.0378	.001031	.000583	.005524	112.1	1190	.00000245	7.9
3	0.1350	.00369	0.3100	3	.1750	.004780	.0535	.001460	.000826	.005606	114.9	1231	.00000299	9.6
4	0.2690	.00735	0.4760	3	.2070	.005650	.1490	.004070	.002300	.007950	174.1	2300	.00000319	10.3
5	0.1655	.004515	0.2510	2	.0855	.002335	.0340	.000929	.000525	.002860	94.5	919	.00000491	15.8
6	0.1320	.00360	0.1915	3	.0595	.001620	.0305	.000833	.000471	.002091	16.6	67.6	.00005320	171.5
7	0.1080	.00459	0.1670	3	−.0010	−.000030	.0241	.000658	.000372	.000342	16.8	68.7	.00006690	216.0
8	6.6900	.18260	6.0500	3	−.6400	−.017500	.4350	.011880	.006710	−.010790	Openings large enough for ordinary flow			

A. Initial absorption of stone in per cent by weight.
B. Initial space in ccs. per cc. of stone.
C. Absorption of stone after treatment in per cent by weight. Treatment consisted of alternate applications of $BaCl_2$ and Na_2SO_4 solutions until the stone was saturated.
D. Number of treatments. The stone was dried out and washed in distilled water after each treatment in order to remove unused solution.
E. Resultant increase in absorption in per cent by weight.
F. Resultant increase in pore space in ccs. per cc. of stone.
G. Actual gain in weight of test cubes under treatment, due to precipitation of $BaSO_4$ in the openings.
H. Actual gain in weight per cc. of stone.
I. Amount of $BaSO_4$ deposited in place of $CaCO_3$ to account for weight and pore-space increase simultaneously. Amount is equal to values in column *H* divided by 1.77 (difference between specific gravity of barite and calcite).
J. Total calcite displaced per cc. of rock as a result of treatment. This is equal to the sum of columns *F* and *I*. This space is the effective space produced for mineralization by saturated solutions.
K. Linear contact between grains for each square centimeter of crystalline limestone. (Method of calculation illustrated by Fig. 5.)
L. Area of contact between grains in one cubic centimeter of crystalline limestone. This value is equal to column *B* divided by column *L*, and is given in centimeters.
M. Width of space between grains.
N. Width of space between grains given in terms of diameter of water molecules.

any zone which could be attributed to surface rupture by crystallization. The amount of pore space in the residue of the cube was determined and found to be identical within limits of homogeneity of the rock with that of the full-sized cube after treatment. (Table IV.) Increased absorption of the treated cubes

TABLE IV.

LOCATION OF INCREASED ABSORPTION OR PORE ENLARGEMENT.

Spec. No.	*A*	*B*	*C*	*D*	*E*	*F*	Type of Stone
3*	696.4180	3.317	0.476	471.308	2.413	0.513	White crystalline ls.
6	684.6745	2.141	0.313	476.766	1.459	0.306	Sulphide bearing marble.
8	699.4900	1.860	0.266	476.864	1.326	0.278	White crystalline ls.

* Same specimen as Spec. 3 in Table III.
A. Weight of entire specimen after treatment with solutions.
B. Weight in grams of water absorbed by treated specimen.
C. Per cent absorption of entire cube.
D. Weight of residual cube after outer faces were honed away.
E. Weight in grams of water absorbed by treated specimen.
F. Per cent of absorption by residual cube. (Central part of treated cube.)

was shown thereby to be almost uniform throughout the stone and should be attributed to amount of $CaCO_3$ dissolved rather than to increase of space by fracturing induced by crystallizing forces. Increased pore space is purely a solution phenomenon, making space for deposition of materials from solution.

Explanation of solution in capillaries.

The surface area of a unit volume of solution increases greatly when the solution enters smaller as opposed to larger openings, but the change assumes exceedingly important magnitude when the smaller openings are capillaries. Also, composition of this solution always alters so as to concentrate at the surface those constituents which have intrinsically the smallest free surface energy. This concentration is called adsorption, and as a general rule the solute is adsorbed or concentrated at the surface if the solution has a lower surface tension than the solvent. Water molecules have a weaker attractive field of force than NaCl molecules and a layer of water comparatively free from salt forms at

the surface of the solution. $BaSO_4$ and $CaSO_4$ behave like NaCl. Finely divided $BaSO_4$ introduced into a solution in contact with coarse $BaSO_4$ crystals or grains is dissolved, and the solute concentration may be raised 80 per cent. The fine $BaSO_4$ has increased the solution surface, and since the surface layer of this increased surface is unsaturated, Ba and SO_4 ions enter it to establish equilibrium. If the solution had a lower surface tension than the solvent (that is, if the water molecules had a stronger attractive field of force than the solute) as seems to be the case in many silica solutions, the solute is concentrated in the surface layer and tends to be precipitated. The same changes occur when the solvent surface is increased by entrance into capillaries.

Langmuir,[9] Goard,[10] Harkins and McLaughlin,[11] and Harkins and Gilbert [12] showed that the thickness of the unsaturated layer varied from less than 2.5 Å in solutions of high concentrations to 5 Å or more in solutions of low concentrations. (The diameter of a water molecule is 3.1 Å). The narrow width, and the variable width of the unsaturated layer is believed to indicate that this layer can hold a variable amount of solute, but that a strong tendency exists for the unsaturated layer to have none of the solute; hence there is also a marked tendency to concentrate all dissolved molecules with high attractive fields of force in the central part of the solution. The unsaturated film is a very small part of the solution where capillaries are wide but may constitute as much as 10 per cent. where capillaries are narrow (Fig. 6). Solution in this new surface film of unsaturated solvent is believed to be the explanation of greater enlargement of openings, and greater metasomatism, in rocks with narrow capillaries than is found in rocks with wide ones, an effect illustrated by Column h, Table III.

[9] Jour. Amer. Chem. Soc., 1917, p. 1897.
[10] Jour. Amer. Chem. Soc., 1925, p. 2451.
[11] Jour. Amer. Chem. Soc., 1925, p. 2083.
[12] Jour. Amer. Chem. Soc., 1926, p. 604.

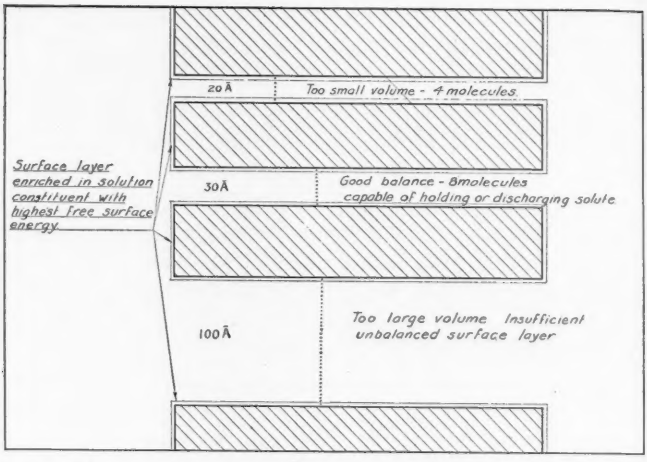
20 Å
Too small volume - 4 molecules
Surface layer enriched in solution constituent with highest free surface energy
30Å
Good balance - 8molecules capable of holding or discharging solute
100Å
Too large volume Insufficient unbalanced surface layer

FIG. 6. Diagram showing the reason for variable efficiency of solutions in capillaries.

Application to Mineral Deposition Studies.

The amount of $CaCO_3$ replaced by $BaSO_4$ in the test pieces is inversely proportional to width of rock openings (Table III); the width of such openings in the very coarse-textured porous crystalline limestone (Spec. 3, Table III) represents the approximate turning point in the experimental work. The very porous limestone (Spec. 8, Table III) had many of the openings slimed over by a deposit of barite. This duplicates localization of metasomatic deposits in rocks of very low porosity. But the most important application of this principle is in replacement phenomena of mineral veins of the epithermal zone. The barite-lead veins of the Connecticut Valley represent this remarkably well and the Leverett, Mass., occurrence is a diagrammatic case.

Metasomatism in the Leverett Barite-Lead Vein.—The Leverett lead vein occupies a fissure in gneiss. Early minerals have been fractured by repeated opening of the fissure during minerali-

zation, but locally barite plates form an unbroken meshwork with open spaces and solid masses immediately adjacent. Microscopic examination of the cellular parts of the vein shows barite plates encrusted with galena and sphalerite, and quartz over both barite and the sulphides. Barite plates are preserved perfectly in open spaces even though both quartz and sulphides encrust them. Idiomorphic plates projecting into the solid masses have their rectilinear outlines preserved at intervals by the encrusting sulphides, but the barite itself is replaced almost completely by quartz. The continuity of cleavages from barite plates into cusped barite remnants indicates former extent of individual crystals.

Solutions have deposited encrusting quartz crystals upon barite plates in the open spaces without etching their surfaces, indicating that the solutions were saturated with barite under conditions existing in large openings. These same solutions continued to deposit quartz along capillary openings such as grain boundaries in the massive earlier deposits in space acquired by solution of barite. These interpretations are in accord with the general reactions of silica-bearing solutions, which seem to indicate that SiO_2 molecules have a lower attractive field of force than water molecules; they are also in agreement with the fact that barite is known to have a higher attractive field of force than water, and solutions saturated in $BaSO_4$ in large openings are unsaturated in it in capillaries. Replacement of barite by quartz at the Leverett locality is so extensive that the replacement quartz appears to belong to a different mineralization stage. The continuous paragenetic sequence of barite, sphalerite, galena and quartz encrusting one another in open spaces, and of barite, sphalerite, galena and quartz replacing one another in sequence in massive parts of the vein only a millimeter away, shows the two types of quartz to belong to the same generation; their differences are due to different conditions of precipitation. In the light of the replacement studies here reported and of the adsorption studies of Langmuir and others, such contrasts between metasomatism along capillaries and simple deposition in large open spaces is entirely expectable.

SUMMARY AND CONCLUSIONS.

Experimental studies of metasomatism in capillaries are in progress, and field studies of solution paths in crystalline limestones, supplemented by laboratory tests of pore space and pore width, are being continued. However, the collected data seem sufficiently indicative of processes influencing metasomatism to merit the attention of students of mineral deposits, and the following tentative conclusions are presented for consideration:—

1. The Bernouilli effect influences mineral precipitation under both the Van't Hoff and Le Chatelier laws.

2. The Bernouilli effect seems to be an important factor in producing banded structure in metasomatic deposits in chemically homogenous rock.

3. In a given *crystalline limestone,* the pore space is greater and the pores wider where the beds are highly deformed on anticlines and in synclines than where the beds are extremely regular.

4. Metasomatism and types of metasomatic minerals are controlled or influenced materially by the adsorption phenomenon studied by Langmuir.

5. Metasomatism may be expected to be developed best in rocks with very narrow capillary openings. Most effective width will vary with the diameter of the molecules in the solution, and is about 30 Å where water, $BaCl_2$, Na_2SO_4, and $CaCO_3$ are involved.

AMHERST COLLEGE,
AMHERST, MASS.,
March 2, 1936.

DISCUSSION AND COMMUNICATIONS

CENTRAL PATRICIA GOLD MINE, ONTARIO.

Sir: In respect to Mr. J. M. Cormie's article on the Central Patricia Gold Mine which appeared in the January–February issue of ECONOMIC GEOLOGY it appears to me that the author is somewhat unfamiliar with the local geology of the area as he has either omitted or given an inadequate description of some structural features of considerable importance in the immediate vicinity of the mine.

The paragenetic relations of the ore and gangue minerals, as shown in the above mentioned paper, also seem to me to be unusual, and unless a more detailed description of them is given than appears in the text of the article, the conclusions regarding their paragenesis are therefore open to question.

In regard to the diabase dike that crosses the property east of the mine workings, Mr. Cormie says that it is probably rather small. Actually the dike is of unusually large size, being around 250 feet wide, and is one of the most prominent geological features of the neighborhood. This dike, from its strike N. 25 W. (the dip is unknown), possibly belongs to the Matachewan series of diabase dikes first described by the late A. G. Burrows[1] at Matachewan Ontario. These dikes are younger than the Keewatin and Algoman (granite) but older than the Cobalt series. The dike, although it is too far east to have any apparent relationship to the ore deposits, nevertheless serves as a marker for an important structural feature in the vicinity (not mentioned by Mr. Cormie). This consists of a fault in the bed of the Crow River about 350 feet north of the mine shaft. Evidence for the existence of this fault comprises intense shearing and accompanying strong hydrothermal alteration of the rocks adjoining the

[1] Burrows, A. G.: The Matachewan Gold Area. Ontario Bur. Mines, 27th Rept., Bull. 34, p. 19, 1918.

river, together with the apparent offsetting of the dike at the place where it crosses the stream. Between a point on the river due north of the shaft, and its intersection with the northern segment of the dike, a distance of 2,000 feet, this fault has a strike of N. 70 E. (astronomic) and a dip of 75 degrees north. Along the river west of the shaft, the fault seems to run more east and west but retains the same dip. The total shift along the fault at its intersection with the dike, appears to be in the neighborhood of 500 feet, that part of the dike south of the river having been moved eastward relative to the part on the north side. It appears to be essentially a strike fault since with the exception of the diabase dike it either coincides in dip and strike with the other rocks involved or cuts them at a small angle. The fault is also about parallel to the first system of shearing mentioned by Mr. Cormie.

In respect to this northwest cross fracturing, besides showing in the iron formation, as described by the author of this article, there is also the following evidence for its occurrence in the adjoining rocks: (1) A jointing or parting showing in places in the greenstone underground; this strikes northwest and dips around 60 degrees northeast. (2) On the north bank of the river 1,100 to 1,200 feet west of the shaft, the schistosity can be seen to turn from a direction nearly eastwest and a dip of 75° north, to a strike of N. 35–40° W. and a dip of 62° northeast. (3) A fault in the eastern part of the mine, which displaces the iron formation, has a northwest strike and a dip of 62° northeast.

At the time of my report on the Central Patricia Mine made in September 1930, it seemed to me probable that these two systems of shearing and fracturing, *i.e.*, the one parallel to the fault and the other striking northwest, had something to do with the ore deposition. I therefore plotted their intersection and found that it agreed closely with the rake (53° east) of the ore bodies as known at that time. The Crow River fault above described also impressed me as a structural feature of importance and on account of the hydrothermal alteration of the rocks in its vicinity, it seemed to me a possible locus for the ore deposits, so that I stressed it considerably in my report, and within the last year drilling on the north side of river has revealed a vein, about parallel to the

fault, and a short distance north of it, which carries encouraging values. From the drill records these values do not appear to be in iron formation.

In reference to the paragenetic relations of the ore and gangue minerals, I gather that Mr. Cormie regards all of the quartz as distinctly later than the auriferous sulphides, arsenopyrite, and pyrrhotite. This is certainly unusual, for my own experience of quartz, is that it is essentially a " persistent " mineral and although a minor quantity may be later than the auriferous sulphide mineralization, the bulk of the quartz is distinctly earlier in all the gold deposits than I have seen.

Unfortunately the author does not make this matter clear either in his photographs of polished sections or in the text of the article. Pyrrhotite he shows to be later than arsenopyrite but in respect to the non-metallic minerals he says " Pyrrhotite commonly contains particles of non-metallic minerals particularly chlorite, but the age relations are not clear, nor are those between the three common non-metallic minerals (presumably quartz, carbonate and chlorite) present in the ore bodies." If such is the case, the conclusion stated, that all the quartz is definitely later than the sulphides, does not seem to me to rest on sound premises.

Before concluding, I may say that the Central Patricia is a very interesting property and in two respects unique amongst the gold deposits of Ontario. First from the fact that although sporadic occurrences are not uncommon in bands of mineralized iron formation, these are the first ore bodies of economic importance that are entirely contained in this rock. Second, on account of the remarkable metallurgical results attained; the ore being of a type that is normally difficult and in some cases impossible to treat by straight cyanide methods. The gold occurs in a state of very fine division, visible colours being practically unknown, and it is closely associated with pyrrhotite and arsenopyrite; two minerals which are commonly refractory to unmodified cyanide treatment. Nevertheless, usual cyanide practice is followed in the milling, and apart from a somewhat high cyanide consumption, 3.2 pounds per ton, a very high extraction is obtained, amounting to a recovery of 97.5 per cent.; which is quite equal to the best results

attained on ores of apparently much more docile character. The unusual metallurgical amenability of these two normally rather troublesome minerals is possibly due to the mode of occurrence of the gold and the nature of the sulphides in question. Where gold occurs in the form of very minute particles embedded in the gangue and sulphide minerals, and of apparently contemporaneous origin, its release is a function of the fineness of grinding, which has a practical limit (in most cases around 90 per cent. through a 325 mesh screen). If, however, the gold, even in a state of fine division, coats fracture planes in the containing minerals and is therefore subsequent in origin, the minerals on grinding break readily along these cracks, thus exposing the gold to the action of solvents, and although not yet definitely proved, it appears probable that this condition exists in the Central Patricia ore.[2] The composition of the two sulphide minerals, pyrrhotite and arsenopyrite, may also have something to do with the matter. The former mineral lies between troilite, FeS, and pyrite, FeS_2, in sulphur content. Pyrrhotite is also somewhat variable in composition, and although all occurrences are much closer to troilite than to pyrite in respect to the quantity of contained sulphur, some have more of that element than others and hence tend to approach the composition of the latter mineral. Pyrite, a saturated and stable compound, is relatively inert in cyanide solution; but pyrrhotite, being unsaturated and therefore less stable is more or less reactive and frequently acts as a cyanicide, or otherwise interferes with extraction. There is, therefore, the inference that the reactive property of pyrrhotite (in cyanide solutions) may vary inversely as the sulphur content of the mineral.

According to W. B. Timm above quoted, arsenopyrite likewise has a variable effect on cyanide solutions. Some occurrences being as inert as pyrite, whereas others are reactive; again this property appears to depend upon the constitution of the mineral in question. It would appear therefore, that these peculiarities open an interesting field for chemical and mineralogical research.

J. A. Reid.

Toronto, Ontario,
May 14, 1936.

[2] W. B. Timm, Metallurgical Division Mines Branch Ottawa, oral communication.

REVIEWS

The Minerals of Franklin and Sterling Hill, Sussex County, New Jersey. By CHARLES PALACHE. Pp. vi + 135, figs. 199, pls. 19, table 1. U. S. Geol. Survey, Prof. Paper 180. Washington, 1935.

When one of the world's leading mineralogists studies and describes the minerals of one of the world's unique and complex mineral localities, a stimulating report is to be expected. The reader interested in either the minerals or the ore deposits of this famous locality will not be disappointed, for he will find a wealth of information written with the freshness and gusto which Professor Palache can so well infuse into mineral descriptions. The author's study of the minerals extended over a period of 25 years, and included examinations of numerous collections, such as the Canfield, the Hancock, the Losey, and the Kemble, all well known to mineral enthusiasts. The data scattered through the literature is also utilized.

Over 140 minerals are described in the paper, 30 of which are not known elsewhere in the world. The major part of the publication is devoted to descriptions of the individual minerals, in many cases accompanied by excellent photographs and drawings of the crystals.

The ore bodies as a whole have a simple mineral composition, with 43 per cent. franklinite, 1 per cent. zincite, 26 per cent. willemite, 5 per cent. silicates such as garnet and rhodonite, and 25 per cent. calcite. In contrast to the simple mineralogy as a whole are the number and variety of minerals present in very minor amount.

The author believes that the ore bodies were formed by metasomatic replacement of the limestone in pre-Cambrian time. The solutions were derived from pre-existing mixed sulphide ore, and deposition took place near the surface under oxidizing conditions. The minerals produced were, probably, the hydrous zinc silicate, calamine, hydrous oxides of iron and manganese, also carbonates of zinc and manganese. Regional metamorphism has caused dehydration and recrystallization of these minerals. This hypothesis is a commendable attempt to account for the unique features of the deposits, and it will be of interest to see whether future work of a quantitative nature will support it. Other hypotheses of origin that have been offered account for only part of the published data. Literally, thousands of ore deposits and mineralizations related to magmatic activity

are known in the world, and so if the Franklin and Sterling Hill deposits were formed by igneous injection, or by contact metamorphism, or by replacement from magmatic solutions, similar deposits would be expected elsewhere. None similar to these have been found, and an unusual mode of origin seems to be demanded for the Franklin and Sterling Hill deposits.

Franklinite, willemite, zincite and calcite are regarded as primary minerals. Tephroite is probably primary. The deposits have been modified by later pegmatites, by hydrothermal veins and by surface oxidation processes.

A complex group of minerals has been formed in the contact zones of the pegmatites. These include "skarn," recrystallization, and pneumatolytic products; more than half the rare minerals of the district belong to this group. The skarn minerals commonly contain zinc, iron, manganese, or all three. Rhodonite is particularly abundant in the skarn at Franklin, and jeffersonite and gahnite at Sterling Hill. The recrystallization has at times produced large, well formed crystals of franklinite, willemite, troostite and zincite. The pneumatolytic products are largely confined to Franklin, and contain some element not normally present in the ore or the pegmatite, such as chlorine, fluorine, boron, arsenic and sulphur, with at times the hydroxyl. These are found in various types of occurrence. They are mingled with and replace skarn minerals and fill definite veins in ore or skarn. Over 40 minerals belong in this group, including such compounds as barylite ($2BeO.BaO.2SiO_2$), cuspidine ($3CaO.CaF_2.2SiO_2$), beryllium vesuvianite, cahnite ($4CaO.Be_2O_3.As_2O_5.4H_2O$), barite, sphalerite and niccolite. The pneumatolytic veins are not sharply set off from the hydrothermal veins. The latter contain over 50 different minerals, including hydrated silicates, arsenates, carbonates and sulphides. Some of these veins may be post-Paleozoic in age.

The minerals that have been formed by surface oxidation are, with one notable exception, of little importance. At one time calamine ore was the chief source of zinc mined at Sterling Hill. Small amounts of calamine and hydrozincite are found in the gossans of veins of sphalerite.

This report probably represents the highest point yet reached by American descriptive mineralogy.

Quantitative mineral variations with respect to structural features would be of much interest, and it is to be hoped that the geologists of The New Jersey Zinc Company will publish some results of their detailed work at these mines.

W. H. NEWHOUSE.

MASS. INSTITUTE OF TECHNOLOGY,
CAMBRIDGE, MASS.

Geophysics. Vol. I, No. 1. Society of Petroleum Geophysics. January, 1936.

If the first number of the new journal of the Society of Petroleum Geophysicists is a fair indication of what future numbers are to be, geophysicists should welcome the journal as a valuable contribution to the literature of their subject, as it promises to collect in one publication much of the material in both theoretical and applied geophysical methods and their results, that might otherwise be scattered through many journals, and other articles that might perhaps find no place of publication.

The present issue of 178 pages contains twelve articles of general interest and eight pages devoted to Society matters. The articles of general interest include among others: a discussion on seismic computation, a report on the use of the dip needle as a magnetometer, a summary of pending patent litigation relating to seismic exploration, an account of the results of magnetic prospecting in Brazil, and several papers of historical interest. Other articles call attention to improvements in the detail of geophysical methods and to new interpretations of observational data.

It is expected that for the present three numbers will appear annually.

W. S. BAYLEY.

Grundriss der Mineralparagenese. By FRANZ ANGEL AND RUDOLF SCHARIZER. Pp. xii + 293. Julius Springer, Wien, 1932.

This is an invaluable volume for the mineralogist, petrologist, and economic geologist. A summary of the contents gives an idea of what is attempted. There are three main subdivisions devoted respectively to rock-forming minerals and their end-products, to the minerals of the ore deposits, and to the bioliths. In each part, the common as well as the accessory minerals are carefully listed with some description of characteristic features. To emphasize the outstanding facts typical of their genesis, these minerals are further grouped into genetic sub-divisions; thus, under "The Minerals of the Ore Deposits," there are such subheadings as "The associates of tinstone" and "The associates of the zinc minerals." Hence the text furnishes an excellent reference on the mineral facies typical of a specific realm, of their genesis and of the end products resulting from their metamorphism (the last term being used in the broader sense, as Van Hise used it).

Especially useful to American geologists are the summaries of viewpoints because written with a continental bias. The lack of extensive footnotes is regrettable since this leaves the reader at least in places unconvinced that the conclusions advocated are not merely those of the authors of the book. Moreover, for all who are not specialists the

source reference is important as making it available respecting further details; to be able to find at best only the name of the scientist and the date of publication of his article is far from sufficient. In this respect the book is a text, rather than a monograph.

Without considering details of fact or theory, the reviewer notes that among the most valuable are the sections on the genesis of primary igneous minerals (pp. 8–33), the highly condensed discussion of magmatic differentiation (pp. 40–45), and the discussion of pressure effects on textural features of minerals (pp. 142–147). Most useful, however, are the general overview which the book affords; the procedure of treating of mineral associations in their larger sense, without losing sight of details; and especially the fact that the book assembles in one work those peculiar characteristics of mineral societies, descriptions of which are otherwise scattered widely through geologic literature.

Finally, although flavored with a strongly European background, the book is by no means one sided, but accomplishes about as much as could be possibly expected in presenting alternative hypotheses to explain most cases.

CHAS. H. BEHRE, JR.

NORTHWESTERN UNIVERSITY,
EVANSTON, ILL.

Soils. Their Origin, Constitution, and Classification. 2d Ed. By G. W. ROBINSON. Pp. 442, figs. 17, pl. 5. Thos. Murby & Co., London, 1936. Price 20 S.

Since the appearance of the first edition of this book 4 years ago (This journal Vol. 28, p. 87) there has been enough advance in the knowledge of soil to warrant the author in materially amending the chapters on clay complex, base exchange, soil moisture and soil classification. Otherwise the volume differs very little from the original edition. The appendix on the method of analysis of soils is omitted, but enough material has been added to the main text of the book to increase its size by 52 pages, and the bibliography by 150 entries. The addition of 5 plates and 5 figures is worthy of note. The exhaustion of the first edition in so short a time is an indication of the book's popularity.

W. S. BAYLEY.

BOOKS RECEIVED.

L. B. RILEY.

Geologic Conditions Governing Sites of Bridges and Other Structures. W. C. MORSE. Pp. 20, pl. 1, figs. 8. Miss. State Geol. Surv., Bull. 27. University, Miss., 1935. A study of sites for a bridge over the Yazoo River; the danger of landslides to highway construction is expounded.

Las Industrias en el Peru, 1936. J. HOHAGEN. Pp. 122, figs. 5. Cuerpo de Ingenieros de Minas del Perú, Bol. 114. Lima, 1936.

Die Blei-Zinkerzgänge am Schauinsland im südwestlichen Schwarzwald. A. KREUTZWALD. N. Jahrb. f. Min., B. Bd. 70, Abt. A, 1935, pp. 234–334. Stuttgart, 1935. Several generations of the same mineral are recognized, such as four generations of sphalerite.

Research Council of Alberta, 16th Annual Report. R. C. WALLACE, director. Pp. 44, pls. 8, figs. 6. Univ. of Alberta, Rept. 33. Edmonton, 1936. Includes discussions on fuels, road materials, natural gas, tufa deposits and the geology of Sounding Creek and Sheerness Coal areas.

The Tuscarora Mining District, Elko County, Nevada. T B. NOLAN. Pp. 36, pls. 2, figs. 3. Univ. of Nevada, Bull., vol. 30, No. 1. Reno, 1936. A district with an estimated total production of ten million dollars from gold and silver lodes. Intrusive and extrusive andesitic rocks have been fractured, altered, and metallized.

The Eruption of Mt. Pelée, 1929–1932. F. A. PERRET. Pp. 125, figs. 72, diagram and chart. Carnegie Institution, Publ. 458. Washington, 1935. A great contribution to the science of volcanology. The study of *nuées ardentes* indicates that they are caused by gas from the vesiculation of the lava.

The Geology of the Lower Awatere District, Marlborough, New Zealand. L. C. KING. Pp. 50, figs. 16, pls. 4, map. New Zealand, Dept. of Scientific and Industrial Research, Geol. Mem. 2. Wellington, 1934. Tertiary stratigraphy and physiography.

The Eocene Sediments of Mississippi. R. E. GRIM. Pp. 240, pls. 3, figs. 25, histograms 66. Miss. State Geol. Surv., Bull. 30. University, Miss., 1936. A detailed study of the Eocene sediments in the State of Mississippi; the character and composition of the sediments, the location and character of their source area, their stratigraphic relations, and their conditions of deposition. The study is important in evaluating possible geologic structures of water, gas, and oil.

Analyses of Canadian Crude Oils, Naphthas, Shale Oil, and Bitumen. P. V. ROSEWARNE, H. MCD. CHANTLER, AND A. A. SWINNERTON. Pp. 21, pls. 2, figs. 3. Can. Dept. Mines, Mines Branch, Publ. 765. Ottawa, 1936.

SCIENTIFIC NOTES AND NEWS

Col. George E. Cole, Director of Mines of Manitoba, has been elected president of the Canadian Institution of Mining and Metallurgy.

F. E. Keep has gone to Western Australia.

F. W. Rohwer is now chief geologist for the Antilles Petroleum Company, Limited (recently organized subsidiary of the McColl-Frontenac Oil Company, Montreal, Canada), 7 High Street, San Fernando, Trinidad, B. W. I.

W. A. J. M. Van Waterschoot Van Der Gracht, of Heerlen, Holland, will deliver a series of three addresses on geology at the University of London, early in 1937.

W. W. Bradley, State Mineralogist of California, Division of Mines and Mining, San Francisco, is recovering from injuries sustained in a recent automobile accident.

S. J. Truscott has returned to England from Morocco.

Adolph Dovre has resigned as district geologist for the Tide Water Oil Company, and will engage in independent geological work in San Antonio, his office being 710 Milam Building.

E. G. Gaylord, of the Standard Oil Company of California, San Francisco, Calif., has been appointed chairman of the American Petroleum Institute's advisory committee on fundamental research on occurrence and recovery of petroleum.

The Fourth Annual Mineral Industries Conference of Illinois was recently held in Urbana. The subjects of coal, clay, clay products, petroleum, rock, and rock products were considered. Mimeographed copies of papers will be available shortly.

Williams & Wilkins Co., of Baltimore, announce a prize of $1000 to discover an author among science workers who can produce a manuscript on any phase of science which combines authenticity and human interest.

The Fourth Annual Conference of the Illinois-Indiana Petroleum Association was held at Robinson, Ill., on June 6. Papers presented were: Geology and the Oil and Gas Possibilities of the Illinois Basin, by J. M. Weller; Seismograph Methods Applied to Finding Oil Structure, by F. W. DeWolf; Demonstration of Core Tests for Permeability, by R. J. Piersol. Operating problems were discussed informally.

Conrad Schlumberger, inventor and leader in geophysics, died in Stockholm on May 9.

Percy E. Barbour, secretary of the Mining and Metallurgical Society of America, announces the removal of the Society's offices to the fourth floor of 90 Broad St., New York.

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